

PROPERTIES OF VISUAL SIGNALS
IMPLIED BY THE DEPENDENCE OF
THE BEZOLD-BRUCKE HUE SHIFTS ON
STIMULUS DURATION, PSYCHOPHYSICAL
METHOD, AND STATE OF
VISUAL ADAPTATION

Dissertation for the Degree of Ph. D.
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ALLEN LOUIS NAGY
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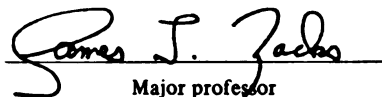
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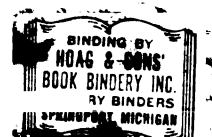
Allen Louis Nagy

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Psychology


Major professor

Date August 2, 1974



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ABSTRACT

PROPERTIES OF VISUAL SIGNALS IMPLIED BY THE DEPENDENCE OF THE BEZOLD-BRUCKE HUE SHIFTS ON STIMULUS DURATION, PSYCHOPHYSICAL METHOD, AND STATE OF VISUAL ADAPTATION

By

Allen Louis Nagy

The effects of psychophysical procedure, stimulus duration, and adaptive state on the Bezold-Brucke hue shifts were examined. The hue shifts are caused by varying the intensity of a monochromatic light while holding its intensity constant. In the first experiment it was shown that stimulus duration is an important variable in determining the qualitative nature of the hue shifts while psychophysical procedure had only a quantitative effect. With short duration stimuli, the hue shifts are non-monotonic with intensity and there appear to be no invariant hues. These results are consistent with the conclusion that with short stimulus duration the response function of the cone systems is non-linear with intensity. With long stimulus duration, the hue shifts are more nearly monotonic and invariant hues do occur, consistent with the interpretation that the response function of the cone systems is linear with intensity. Results of the second experiment show that the lines of constant hue are shifted without change of shape to higher stimulus intensities as a result of light adaptation to an achromatic background. This result is consistent with the notion that the effects of a change in adaptive state can be characterized in terms of a scalar gain control mechanism which rescales the visual signal prior to the point at which the signal becomes non-linear with intensity.

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DEPENDENCE OF THE BEZOLD-BRUCKE HUE SHIFTS ON STIMULUS
DURATION, PSYCHOPHYSICAL METHOD, AND STATE OF VISUAL ADAPTATION

By

Allen Louis Nagy

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INTRODUCTION

One of the classical problem areas in visual science has dealt with the nature of the function describing the relationship between visual response and stimulus intensity. The general class of problems includes at least two subclasses. One of these deals with the relation between the magnitude of perceptual response and physical stimulus intensity. Fechner's Law and Stevens' Power Law are classical examples of this class. Both deal with the relation between perceptual brightness and stimulus intensity.

The second subclass deals with the relation between internal response of the visual system and stimulus intensity. The magnitude of a perception need not be directly involved in these problems. A good example of this kind of problem appears in the literature on the phenomenon known as the Bezold-Brucke Effect, the change in hue of a monochromatic light caused by varying its intensity. This effect has been explained in terms of the nature of the function describing the internal visual response with intensity. This type of argument has been carried to sophisticated levels recently by Krantz (1974) and Savoie (1973). In what follows some of this work will be described along with two experiments. The first experiment was done to resolve some conflicts in results of recent experiments on the form of the hue shifts. The second experiment examines the effect of light adaptation on the hue shifts. These results are discussed in terms of two classes

of models of light adaptation; passive, response compression models and active, scalar gain control models. Both experiments are directed at examining the manner in which visual response varies with stimulus intensity.

EXPERIMENT I

Because of the importance of the relationship between stimulus intensity and the response of the visual system at various levels, many different methods and models have been used to arrive at response functions thought to underlie the relation of perceptual brightness and detection to stimulus intensity. A good example of one type of approach to this problem is a model for Weber's Law behavior in an increment threshold task presented by Cornsweet and Pinsker (1965). One of the crucial aspects of their model is the deduction that the physiological visual signal at some level is logarithmically related to stimulus intensity. This paper is a particularly good example of a model-bound type of approach in which the nature of the relation between visual response and stimulus intensity is used to explain a visual phenomenon.

An analogous approach to the intensity-internal response problem has arisen in color vision work in attempts to account for the phenomenon known as the Bezold-Brucke Effect. The Bezold-Brucke Effect is the change in hue of a monochromatic light caused by varying its brightness. (Evidence that stimulus brightness is the crucial variable rather than the quantum catch is presented in Koren and Kieth, 1970.) The first empirical description of the phenomenon was reported by Purdy (1931, 1937). Figure 1 shows Purdy's results. Wavelength is plotted along the abscissa and luminance along the ordinate. Each line is a

Figure 1.--Lines of constant hue in a wavelength-intensity space. Redrawn from Purdy (1937). Each point on a given line matches each other point on that line in hue. Arrows indicate the location of the invariant hues.

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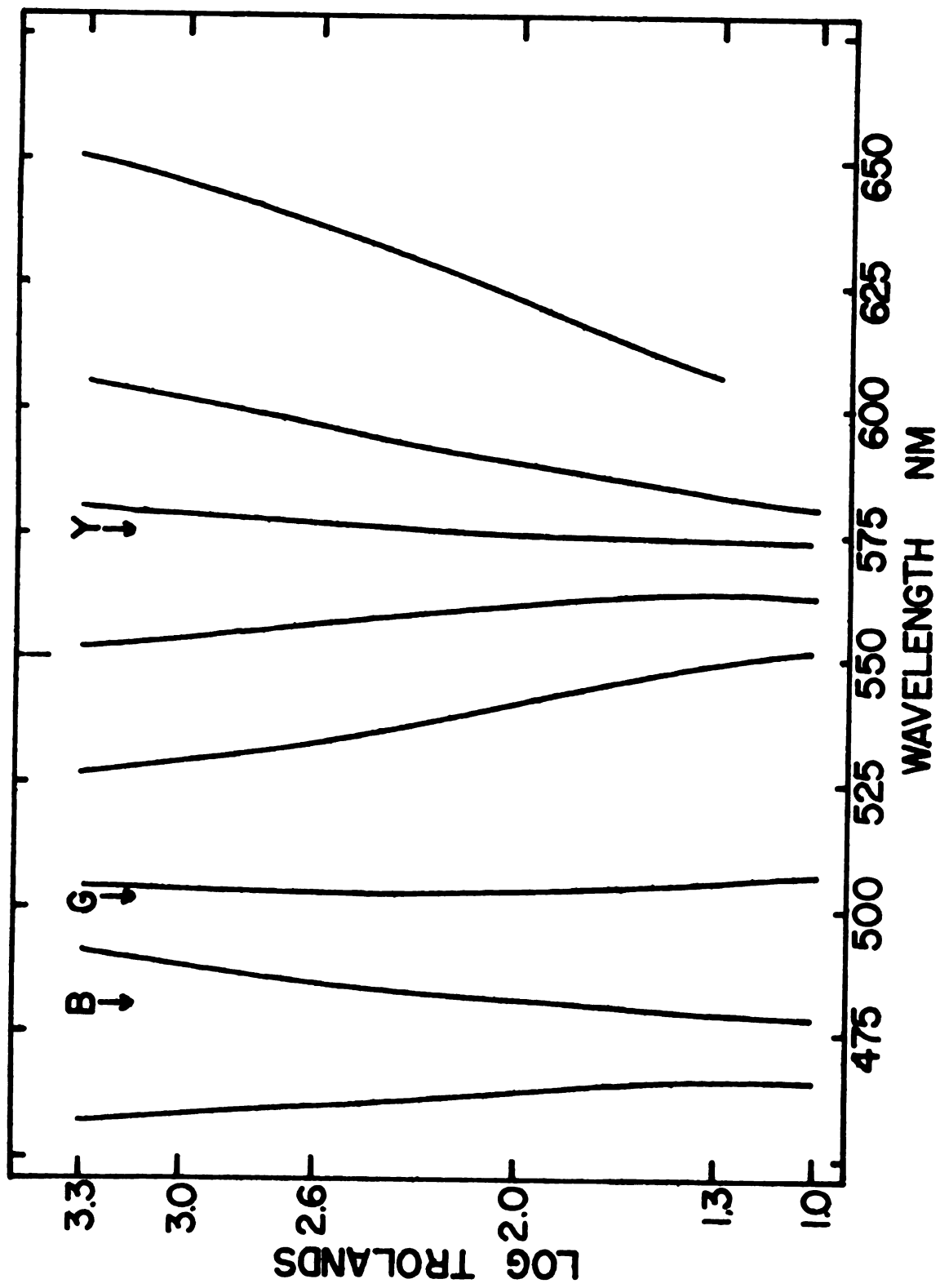


FIGURE 1

line of constant hue. That is, the hue of each point on a given line matches the hue of each other point on that line. It is clear that with changing luminance, wavelength must usually be changed in order to keep hue constant. Three characteristics of these data should be noted here. First, there are a few points in the spectrum, marked by arrows in the figure, at which hue does not appear to change with intensity. These were called invariant hues by Purdy. Second, hue appears to vary monotonically with intensity. That is, the lines of constant hue do not change direction anywhere along their extent. Third, the data suggest that reds and greens predominate at low intensity and blues and yellows at high intensity. An illustration of this can be seen in the yellow region of the spectrum where a wavelength that appears reddish orange at low intensity appears much more yellow-orange at high intensity. Similarly, green wavelengths at low intensity become greenish yellows at high intensity.

Purdy followed the suggestions of von Helmholtz (1924) and C. S. Pierce (1877) in presenting an explanation based on the nature of the relation of visual response to stimulus intensity. From the Young-Helmholtz theory, hue is a function of the ratios of the activities in three independent receptor systems. Purdy, as did Pierce and Helmholtz, assumed that the response in the three systems increased with intensity "not in direct proportionality, but according to a law of diminishing returns."* That is, a fixed increment in intensity produced a greater increment in response at low intensities than at high intensities. This type of function is sometimes called a "response compression." Purdy showed that, within the Young-Helmholtz theory, the

*Purdy, 1931, pg. 543.

assumption of identical "response compressions" for the three cone systems could qualitatively predict most of the empirical data. Invariant hues should occur at wavelengths that excited two of the receptor systems equally, since an increment in intensity would produce equal increments in the responses of the two systems. However, Purdy noted a major difficulty with the trichromatic explanation. At very low intensities, all hues ought to shift toward the three "primary hues" of the three receptor systems, red, green, and blue. The hues of long and middle wavelengths behave as expected shifting toward red and green, respectively. But the hues of short wavelengths shift away from blue with decreasing intensity, rather than toward it.

The inability of the trichromatic explanation to account for short-wavelength hue shifts eventually prompted an opponent-process explanation (Judd, 1951). In the Hurvich-Jameson opponent-process color model, the response outputs of the opponent mechanisms are thought to underlie both the hue shifts and the existence of invariant hues (Hurvich and Jameson, 1957). A schematic of the model is shown in Figure 2. Three different types of cones, with differing spectral sensitivities, absorb quanta of light and generate neural responses which are eventually fed into the opponent-process mechanisms where they are algebraically summed. These are called opponent mechanisms because there are antagonistic combinations of the cone system outputs. While the input from one type of cone is excitatory, the input from another type of cone is inhibitory. Since the three cone systems have different spectral sensitivities the output of the opponent mechanisms will vary as the wavelength of the light is varied. Thus such a mechanism is capable of coding hue. Two opponent mechanisms are shown

Figure 2.--Schematic representation of the Hurvich-Jameson Opponent Process Model of color vision. Spectral sensitivity curves of the cones and the opponent mechanisms are shown at the upper and lower right respectively. The two mechanisms on the far left are color-coding mechanisms while the mechanism on the right is a whiteness or brightness mechanism.

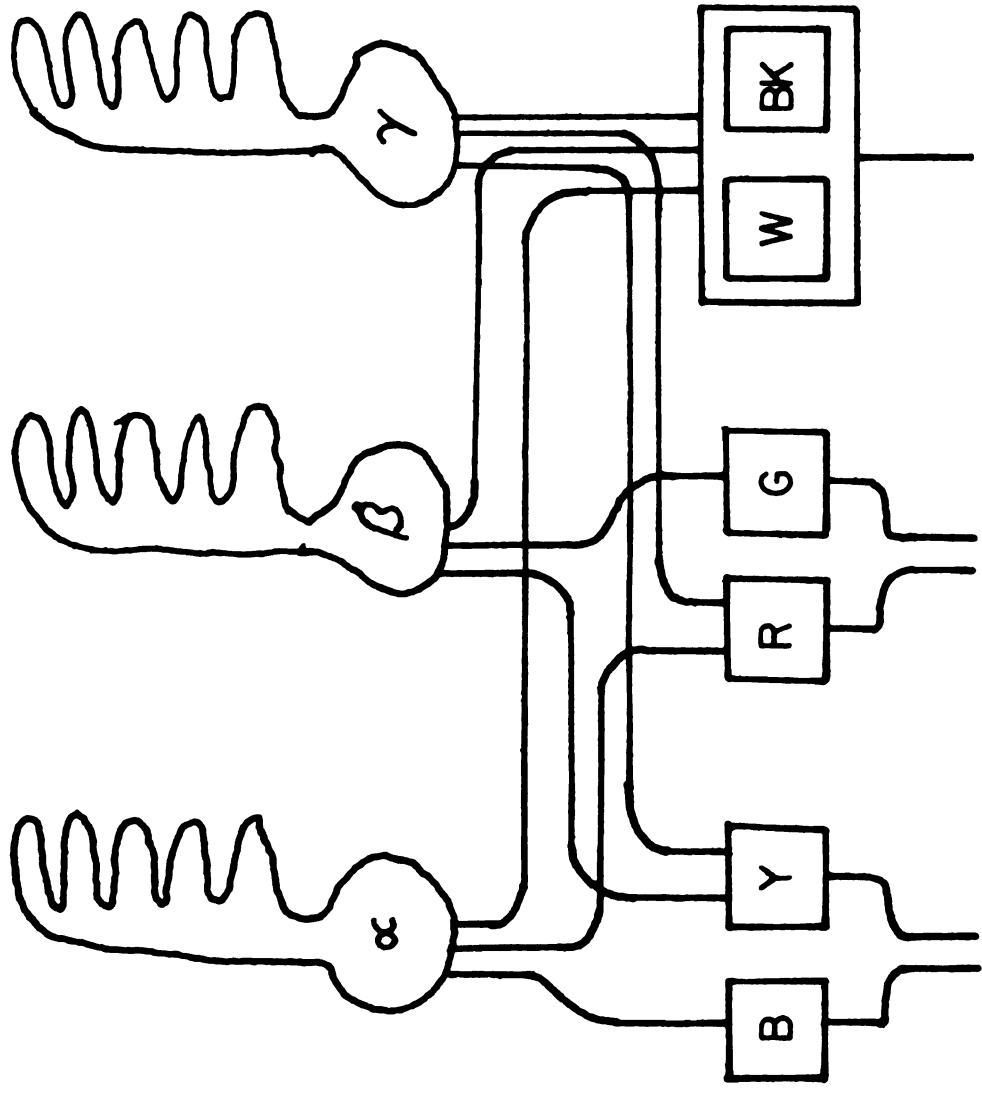
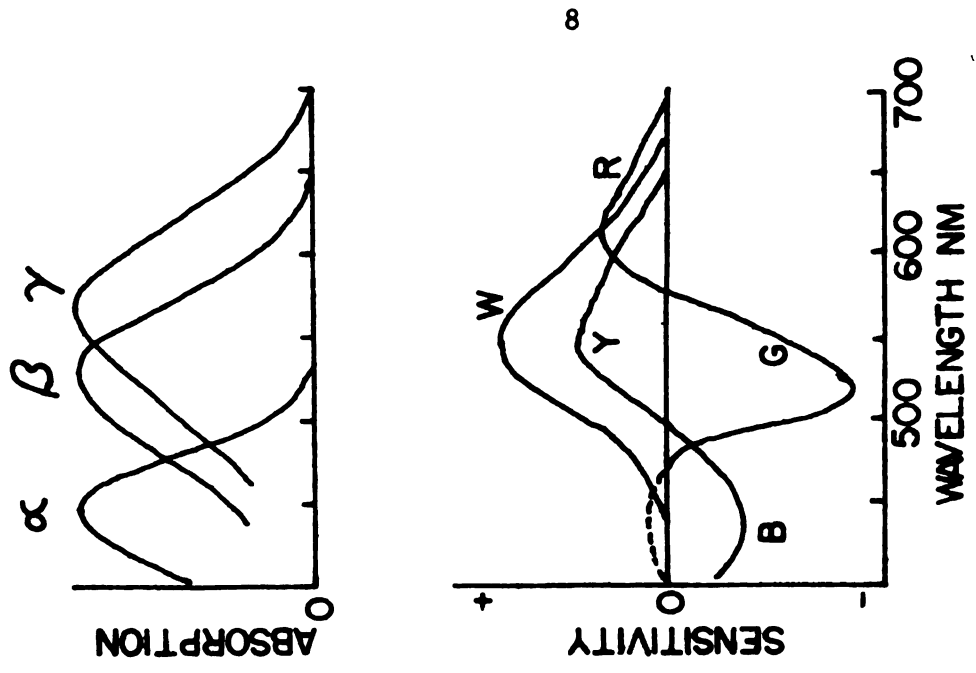


FIGURE 2

on the left in Figure 2. The third mechanism on the right is not opponent in the same manner, but simply sums the inputs of the three cone systems to produce a brightness signal.* Spectral sensitivities of the cones and the three opponent mechanisms are shown to the right. The physiological existence of opponently organized color mechanisms in primates is supported by the work of DeValois (1965) and Wiesel and Hubel (1966), although thus far these investigations do not provide detailed quantitative support for any specific psychophysical opponent process theory.

The hue shifts are explained within the model by assuming that there are two opponent systems, one which signals blue and yellow and another which signals red and green. The input signals from the cone systems are assumed to be linear with stimulus intensity. The outputs of the opponent mechanisms are influenced by luminance such that the blue-yellow response increases with intensity at a greater rate than red-green response. Hue is assumed to be related to the ratio of the responses in the red-green and blue-yellow outputs. Hurvich and Jameson have shown (1957) that such a model predicts the predominance of red and green hues at low intensity and blue and yellow hues at high intensity in Purdy's data. The occurrence of invariant hues is also a necessary consequence of the theory. Whenever the cone inputs to one of the opponent mechanisms algebraically sum to zero, a "unique" yellow, blue, green, or red is seen. The term "unique hue" simply refers to those hues at which only one of the opponent mechanisms is

*The black-white mechanism is opponent in the sense that white induces blackness in neighboring areas. Thus lateral interactions such as those occurring in the Mach band effect may be characterized by the opponency of the black-white mechanism.

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active. For example, unique yellow occurs when only the yellow system is active and the red-green mechanism is at zero or at equilibrium. When an opponent mechanism is inactive or at equilibrium, its output cannot be influenced by luminance. Hence, the hue of the stimulus will not change with intensity since the ratio of the outputs of the two opponent mechanisms will remain at either zero or infinity. The "unique hues" must necessarily be invariant hues.

In the context of this model it is possible to ask about the relation of the cone system response to stimulus intensity and also the relation of the opponent-mechanism response to stimulus intensity. For example, Larimer, Krantz, and Cicerone (1974) have shown that within the framework of the opponent mechanism model it can be shown that the cone system response functions must necessarily be linear with intensity if two empirically determinable properties are true. The necessary assumptions of the model are: Assumption 1. The linear combination of the cone system inputs and the output of the red-green opponent mechanism, f_1 , is described by the equation:

$$f_1 = K_1 \alpha^{n_1} - K_2 \beta^{n_2} + K_3 \gamma^{n_3}$$

where: f_1 is the output of the red-green mechanism and may embody a monotonically increasing function, linear or non-linear.

$K_1 > 0$ is a weighting factor describing the relative contributions of the cone systems.

$$1 > n_i > 0 \quad i = 1, 2, 3$$

and α, β , and γ are quantum catches of the short, middle, and long wavelength cones.

There are many other possible forms of this equation that can be used to derive linearity. Some of them are listed in Larimer, Krantz, and

Cicerone (1974). The blue-yellow mechanism is also described by a similar equation but only the red-green mechanism and unique yellow will be discussed here. Assumption 2. f_1 must have a value of zero (e.g., the red-green mechanism is inactive) at unique yellow and unique blue.

If it can be shown empirically that unique yellow and unique blue are invariant with intensity, then it must necessarily be true that all the n 's be identical in value (e.g., $n_1 = n_2 = n_3$). That is, the three cone response functions must be the same shape. Any other possible relationship between the n 's requires that either the assumptions of the model are wrong, or that the wavelengths of the unique hues vary with intensity. If, empirically, any additive combination of unique yellows and unique blues results in another hue unique with respect to the red-green opponent mechanism (e.g., a unique yellow, a unique blue, or white), then all the n 's must equal 1 (e.g., $n_1 = n_2 = n_3 = 1$). That is, response in the three cone systems must be linear with stimulus intensity. Any other value for n requires that either the assumptions be wrong, or that the additive combination produce a non-unique hue.

Larimer, Krantz, and Cicerone have found empirically that unique blue and unique yellow are invariant with intensity and that additive combinations of unique blue and unique yellow do, indeed, produce another unique hue. Thus, cone system inputs to the opponent mechanisms must be linear with intensity if the model is accepted. Linearity of the cone response with intensity, by itself, predicts that no hue shifts should occur at any wavelength. That is, this formulation provides no explanation for hue shifts, but requires that they be the result of processes at the level of the opponent mechanism output or beyond.

On the other hand, Savoie (1973) recently reported an experiment in which he apparently failed to find an invariant hue in the yellow region of the spectrum. Although Savoie made no attempt to directly determine a hue shift curve at unique yellow, he did determine curves at several wavelengths in the yellow region of the spectrum. His results are shown in Figure 3. His results differ qualitatively from the classical results of Purdy in that hue does not vary monotonically with intensity. One cannot reasonably infer the presence of an invariant hue (which would be represented by a straight vertical line) in this region as one can in Purdy's data (see Figure 1). Savoie's analysis of the results implies a non-linear relation between stimulus intensity and the cone system input to the red-green opponent mechanism, the original Pierce-Helmholtz explanation.

Since the conflicting results in these recent experiments are important to color vision models and to the nature of the response vs. intensity function, an experiment was designed to examine the reasons for the disagreement. There are two major differences in the Savoie and Krantz studies which seem to be likely candidates. First, Savoie used a very short stimulus duration of only 5 msec. while Krantz used a 1-second stimulus exposure. Secondly, Savoie used a hue matching procedure which required the observer to match the hue of two stimuli of different intensities while Krantz used a procedure which required the observer to set the hue of a single stimulus to unique yellow. Both procedures were used here with short (10 msec.) and long (300 msec.) stimulus durations in order to determine whether flash duration or the nature of judgment the observer was required to make, determined the



Figure 3.--Lines of constant hue derived from Savoie's method of matching. Redrawn from Savoie (1973). Again each point on a given line matches each other point on that line in hue. Notice that these curves are non-monotonic and there appears to be no invariant hues.

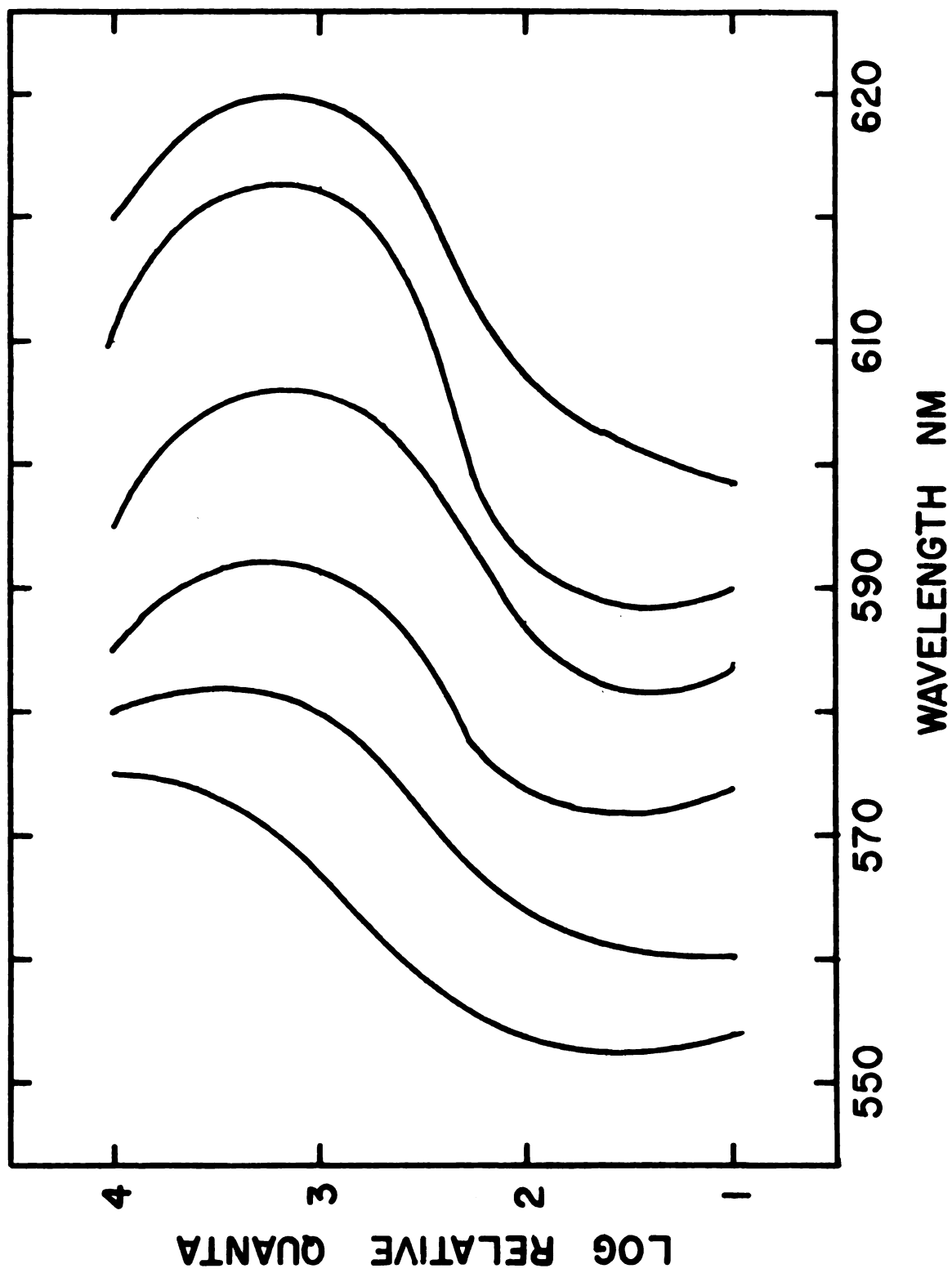


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results. The 10 msec. flash is assumed to be equivalent to Savoie's 5 msec. flash and the 300 msec. flash roughly equivalent to Krantz's 1-second flash. The basic design was thus a 2 x 2 matrix, psycho-physical task x flash duration, shown in Figure 4.

METHOD

APPARATUS.

A three-channel optical system (diagrammed in Figure 5) was used to present the stimuli to the observer in Maxwellian view. A single tungsten iodide coil-filament lamp (GE, #Q6.6A/T2½/CL, 6.6 amp, 45 watt) driven by a well-regulated DC power supply provided the illumination for all three channels. This arrangement minimized variation of one channel with respect to the others. Slight variations in the intensity of the lamp over time would have much less consequence as a result. Two channels, A and B, produced the hue stimuli, while the third channel, C, produced the fixation point. Two Bausch and Lomb chromatic interference wedges were placed at the focal points of lens L_1 and L_4 . Placement at a focal point insured uniformity of hue across the spatial extent of the stimuli. Each wedge was moveable in a direction perpendicular to the optical path to allow selection of a waveband. Wedge B was set by hand to produce standard passbands with peak wavelengths of 570, 580, and 590 nm. Wedge A, mounted on a motor-driven slide controlled by a LINC mini-computer, determined the wavelength of the comparison stimulus.

The beam-splitting cube, C, directed the collimated beams from the two channels on parallel paths to the observer's eye. An electromagnetic shutter, also controlled by the LINC, was placed at the focal

Figure 4.--The design of Experiment I, a comparison of psycho-physical procedures and stimulus durations.

		DURATION	
		10 MS	300 MS
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	JUDGE		

FIGURE 4

Figure 5.--A schematic diagram of the three-channel Maxwellian View optical system used to measure the Bezold-Brucke Effect. Channels A and B produced the hue stimuli and Channel C produced the fixation point.

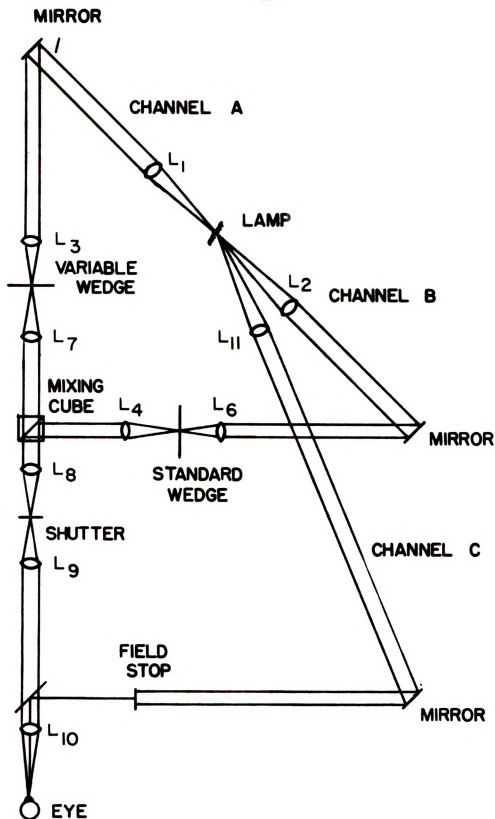


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point of lens L_8 . The shutter produced an almost square-wave light pulse, the rise and fall times being approximately one and two msec., respectively.

Lens L_{11} in channel C collimated a beam of white light which was directed to lens L_{10} by a mirror and a microscope cover slip, S. A stop placed in channel C at the same optical distance as the stimuli produced a tiny fixation point, which was at a just visible luminance. Lens L_{10} formed filament images through each channel on the observer's pupil. Figure 6 shows the appearance and dimensions of the stimuli. In the sessions involving judgment of unique yellow, the standard stimulus, on the left, was blocked and only the stimulus on the right was presented.

Wavelength calibration of the chromatic interference wedges was done by inserting mercury and sodium arc-lamps of known wavelengths into the system and determining the wedge position of maximum transmission with a photo-multiplier tube. These positions were taken as reference points and a spectrometer was then used to determine the wavelengths at other wedge positions. Bandwidths determined by visual inspection with the spectrometer were approximately 12 nm. This bandwidth measure is a rather crude measurement and should not be taken too strongly.

Flicker photometry was used to equate the luminances of the two channels and to equate the luminances of the stimuli at different wavelengths. Wratten neutral density filters could be inserted in the channels to make the necessary intensity manipulations. Neutral density filters mounted on a motor-driven wheel controlled by the LINC also corrected for luminance variation with changes in the wavelength of

Figure 6.--Representation of the stimulus pattern showing two disks
of light and the fixation point.

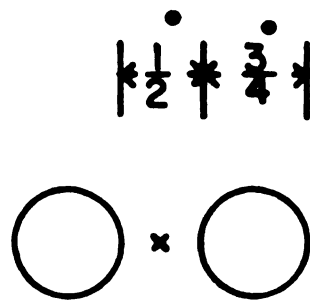


FIGURE 6

comparison stimulus. The retinal illuminance was measured at 580 nm. by making a heterochromatic match with an SEI photometer using the method described by Westheimer (1966).

A bite-bar mounted on an adjustable X-Y-Z positioner held the observer's head rigidly in position. The mini-computer was programmed to operate the equipment and also to collect and save the data.

PROCEDURE.

The equipment was warmed up for thirty minutes at the beginning of each session. Upon entering the light-tight experimental room, the observer dark-adapted for fifteen minutes, a period shown to be sufficient for complete photopic dark adaptation (Cornsweet, 1970). To begin a "run" the subject pressed the response switch. Broad-band noise was delivered through earphones to mask equipment noises. The white noise went off 1/2 second prior to stimulus presentation and resumed after a response was made. An interstimulus interval of 10 seconds was used since Savoie (1973) had found this period to be adequate to prevent interaction between successive stimuli. At the end of the "run" the noise went off, signalling the completion of the run.

The observer's task was always to make a two-choice forced-choice judgment. The two possible judgments were "redder" or "greener." In the matching conditions the judgments were made with reference to the hue of the standard stimulus. In the unique yellow conditions the judgments were made with reference to an internalized conception of what pure yellow was. Responses were made with a double throw toggle switch.

The wavelength of the comparison stimulus was determined according to the rules of a double random staircase procedure, or method of

tracking (described in Cornsweet, 1962). If the observer responded "greener" to a given comparison stimulus the wavelength of the next comparison stimulus from that staircase was decreased. If he responded "redder," the wavelength of the next stimulus from that staircase was increased. The size of the wavelength increment was determined according to the following rules. The initial increment was 10 nm. When a reversal of response was made (for example, "redder," "redder," "redder," "greener"), the increment was reduced to 5 nm. After two more response reversals, the increment was made 2 nm. Then, twelve more stimuli were presented to complete the staircase. Two staircases were run simultaneously, the choice of which staircase the next stimulus was to come from being randomly determined. The values for the wavelength of the comparison stimulus to be presented were calculated independently for each staircase. This procedure made it impossible for the observer to anticipate the next stimulus. One of the two staircases was started 15 nm. above the standard stimulus and the other, 15 nm. below. For the unique yellow conditions the starting points were arbitrarily set at 565 and 595 nm. When twelve 2 nm. increments had occurred in each staircase, the "run" ended. This procedure and the methods used are a replication of Savoie (1973) in most respects.

From six to nine "runs" were made in each experimental session, taking from 1 to 1½ hours. The standard wavelength remained the same throughout a session, while intensity was manipulated. In matching conditions the luminance of the comparison stimulus was always .4 log units greater than the standard. This difference was maintained while the luminance of both stimuli was varied over a 2.5 or 3.5 log unit range in .5 log unit steps. Three wavelengths, 570, 580, and 590 nm. were

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used as standard wavelengths. These wavelengths were chosen to bracket the region of the unique yellow hue which was of primary interest here. At least two runs or four staircases were run at each condition.

SUBJECTS.

Three males served as observers in the experiment. All had some knowledge of the nature of the experiment, but all were naive as to their own performance during the course of the data collection at a particular condition. All subjects had normal color vision as determined by the Farnsworth 100-Hue Test and the H-R-R Pseudoisochromatic Plates. Each subject had an extensive amount of practice, at least ten hours, on each type of judgment before actual data collection began.

RESULTS

It will be shown that the results of the experiment clearly support the notion that stimulus duration is responsible for the qualitative differences between the Savoie and Krantz data. Figure 7 shows an example of the computer printout of the data from a single run. The data from each of the two staircases has been grouped together. The last twelve wavelength values from each staircase were averaged to produce a mean value for each staircase. At least four staircases were run at each condition. Then the mean of the four staircase means was computed. Thus each data point in the following graphs is the mean of at least forty-eight judgments.

Figure 8 shows the results of the judgment of unique yellow procedure, the procedure used by Krantz. Each point on the graph represents the wavelength judged to be unique yellow at a given intensity by the observer. Data for all three observers are shown here. The

Figure 7.--Sample computer printout of the data from a single run.
Data from the two independent staircases are grouped.
A number 3 in the response column indicates a response
of "greener" and a number 2 indicates a response of
"redder". Means of the last twelve wavelengths are
shown at the bottom of each column.

RUN 331 BN 732 ALLEN NAGY DISSERTATION

NAME:DAVE :
 DATE
 : 05120174 :
 :
 STANDARD
 : 590:
 INTENSITY
 : 15 :
 BACKGROUND:0 :
 RUN:331:
 RV
 : 0:
 COMMENT
 : 590MATIONS-D4 :

STAIR 1		STAIR 2	
NM	RESP	NM	RESP
605	3	575	2
595	3	585	2
585	2	595	3
590	3	590	3
585	3	585	3
<u>580</u>	2	580	2
<u>582</u>	2	<u>585</u>	3
584	2	583	2
586	2	585	2
588	3	587	3
586	2	585	2
588	3	587	3
586	3	585	2
584	2	587	3
586	3	585	3
584	2	583	2
586	3	585	3
<u>584</u>	3	583	2
585.3		<u>585</u>	3
		585.	

FIGURE 7

Figure 8.--Wavelength of unique yellow plotted in a wavelength-intensity space. Data for three observers at both short (upper panel) and long (lower panel) stimulus duration is shown. Horizontal lines with vertical hash marks indicate 80% confidence intervals for each point. Notice that the curves in the upper panel resemble Savoie's data and those in the lower panel resemble Purdy's data.

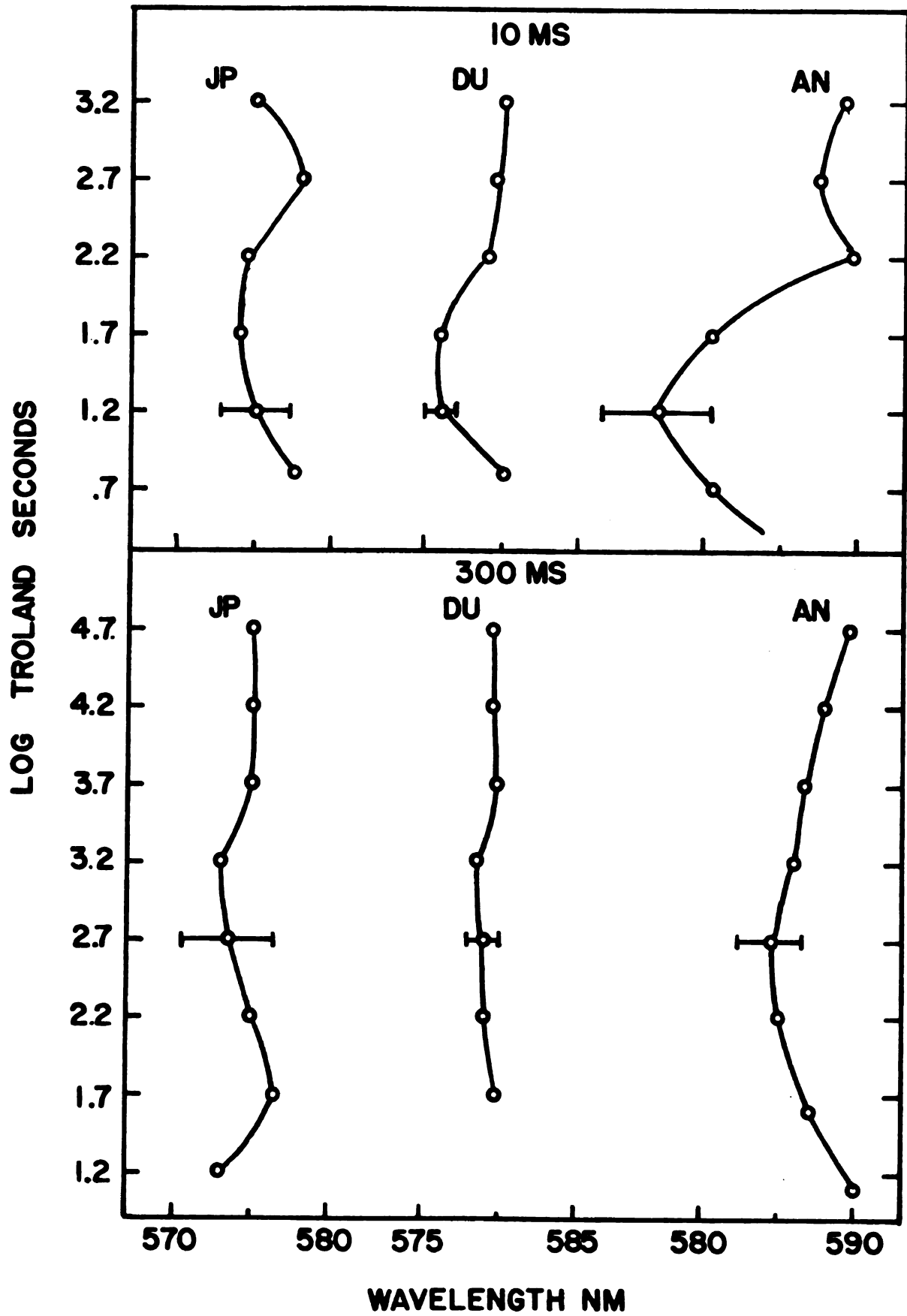


FIGURE 8

upper panel shows the results at 10 msec. and the lower at 300 msec. Wavelength is scaled along the abscissa and retinal illumination is scaled along the ordinate in log troland seconds. The horizontal lines with hash marks at either end indicate 80% confidence intervals based on the variability of the staircase means.

The important point here is to compare the curves for each subject at short and long durations. The results are consistent across observers. In each case the line becomes more nearly a straight vertical line, or invariant hue, at long duration. At the short duration, for two of the three observers, the wavelength of unique yellow varies significantly with intensity. For the third observer, JP, the points fall within the range of variability so that these might be interpreted as a straight vertical line.

Figures 9, 10, and 11 show the data from the matching procedure (Savoie's procedure) for observers AN, DU, and JP, respectively. Again, the results at short duration are shown in the upper panel and long duration in the lower panel. Wavelength is scaled along the horizontal axis and illumination along the vertical axis, again in log troland seconds. The upper end of each line segment is located at one of the standard wavelengths - 570, 580, or 590 nm. The lower end of each segment is located at the wavelength of the comparison that matched the standard, which was .4 log units more intense. The horizontal lines with vertical hash marks again indicate 80% confidence intervals based on the staircase means. Each set of line segments for a particular standard shows a characteristic change in going from low to high intensity at short duration. At low intensity the slopes of the segments are negative; at middle intensities, positive; and at high intensities,

Figure 9.--Line segments connecting points of equal hue in a wavelength-intensity space, determined from the hue matches of Observer AN. Horizontal lines with vertical hash marks indicate 80% confidence intervals. The data in the upper panel were collected with a stimulus duration of 10 msec. and those in the lower panel at 300 msec.

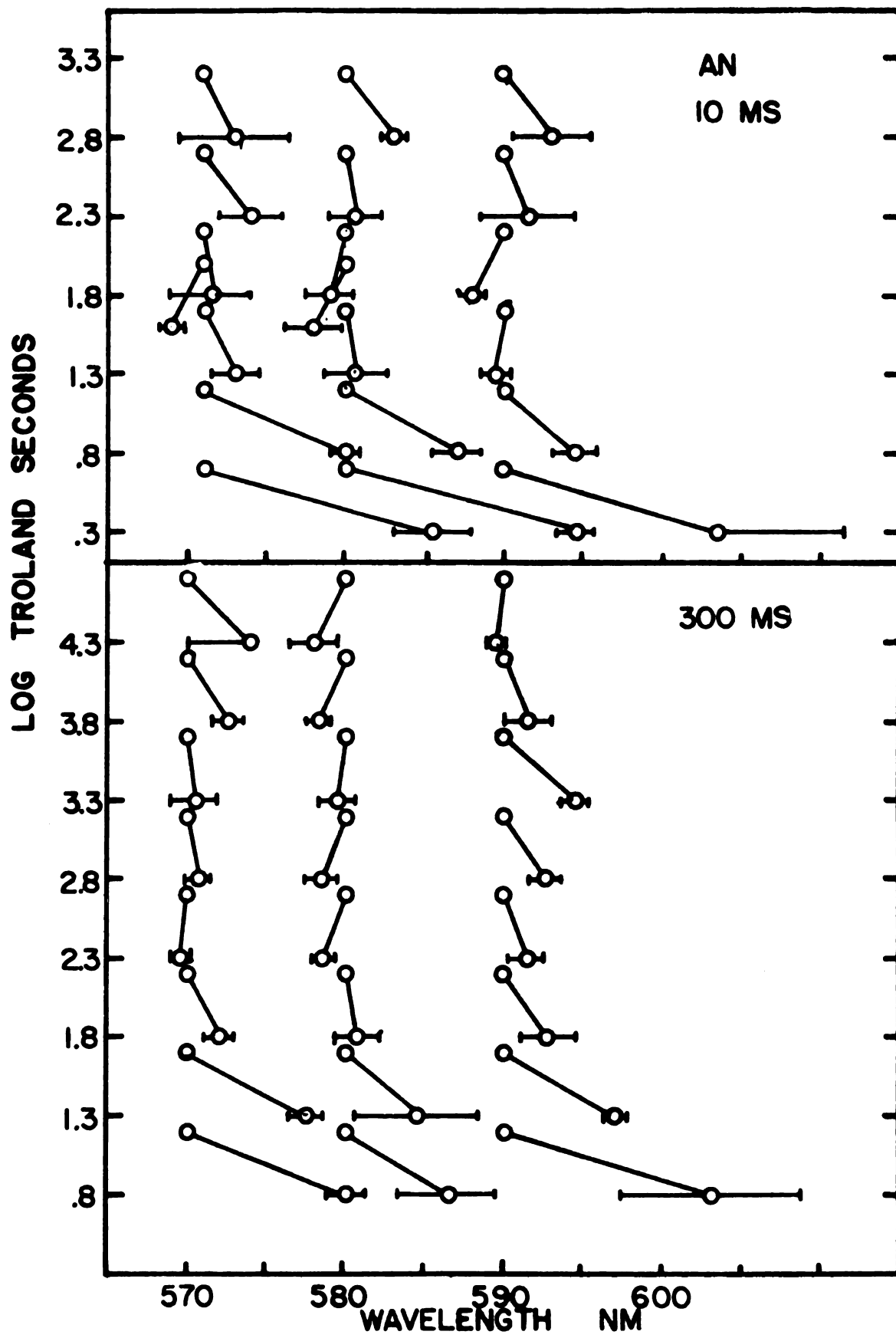


FIGURE 9

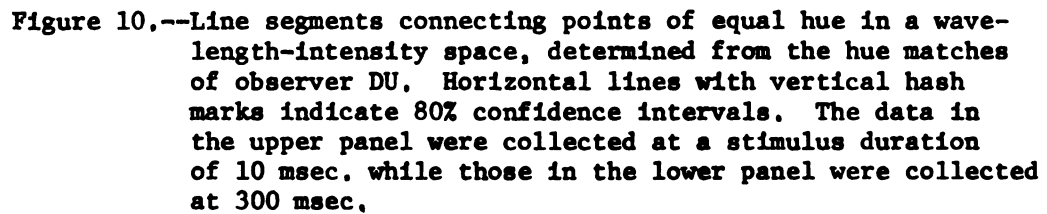


Figure 10.--Line segments connecting points of equal hue in a wavelength-intensity space, determined from the hue matches of observer DU. Horizontal lines with vertical hash marks indicate 80% confidence intervals. The data in the upper panel were collected at a stimulus duration of 10 msec. while those in the lower panel were collected at 300 msec.

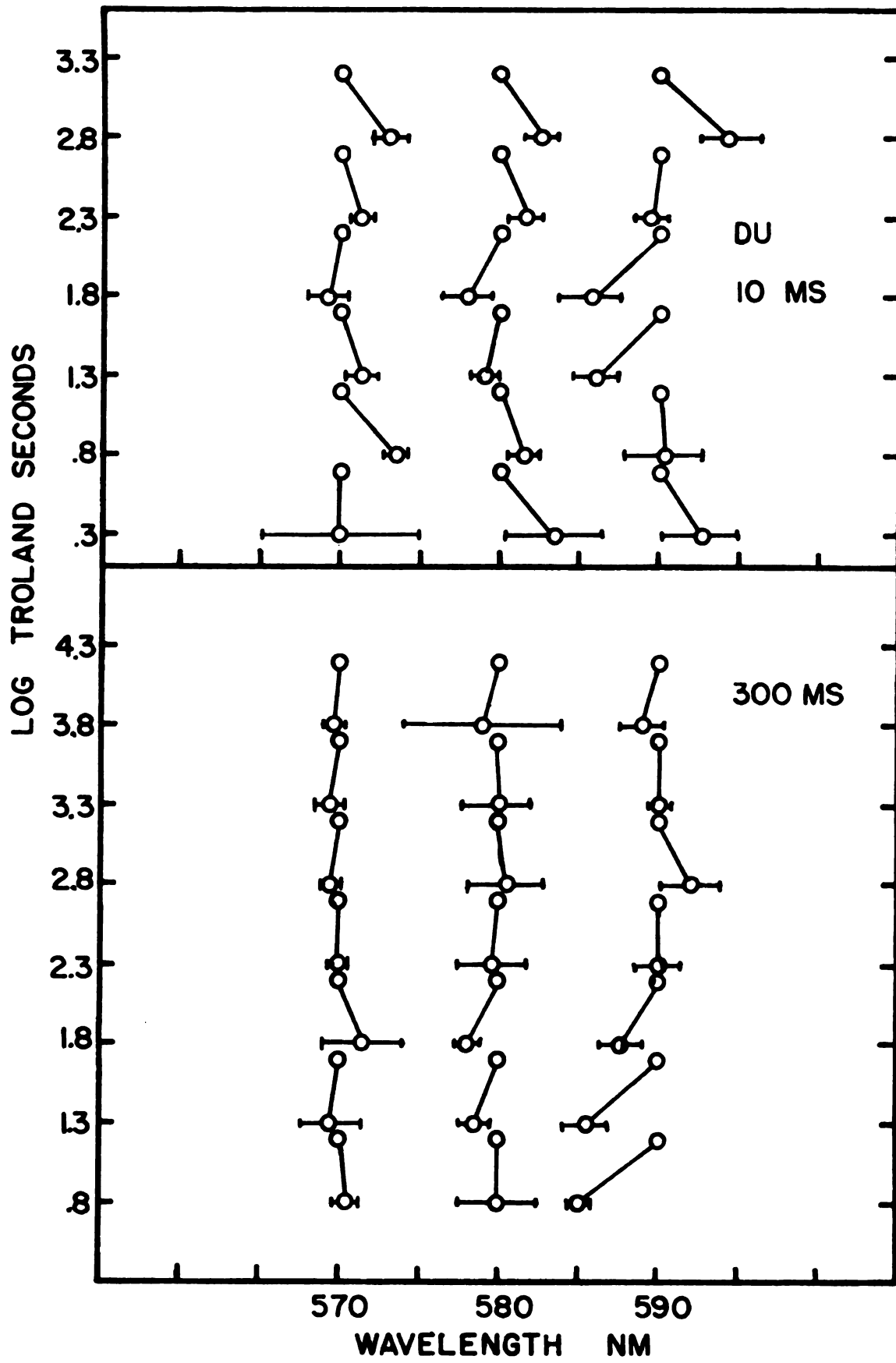


FIGURE 10



Figure 11.--Line segments connecting points of equal hue in a wavelength-intensity space, determined from the hue matches of Observer JP. Horizontal lines with vertical hash marks indicated 80% confidence intervals. The data in the upper panel were collected with a stimulus duration of 10 msec, while those in the lower panel were collected at 300 msec.

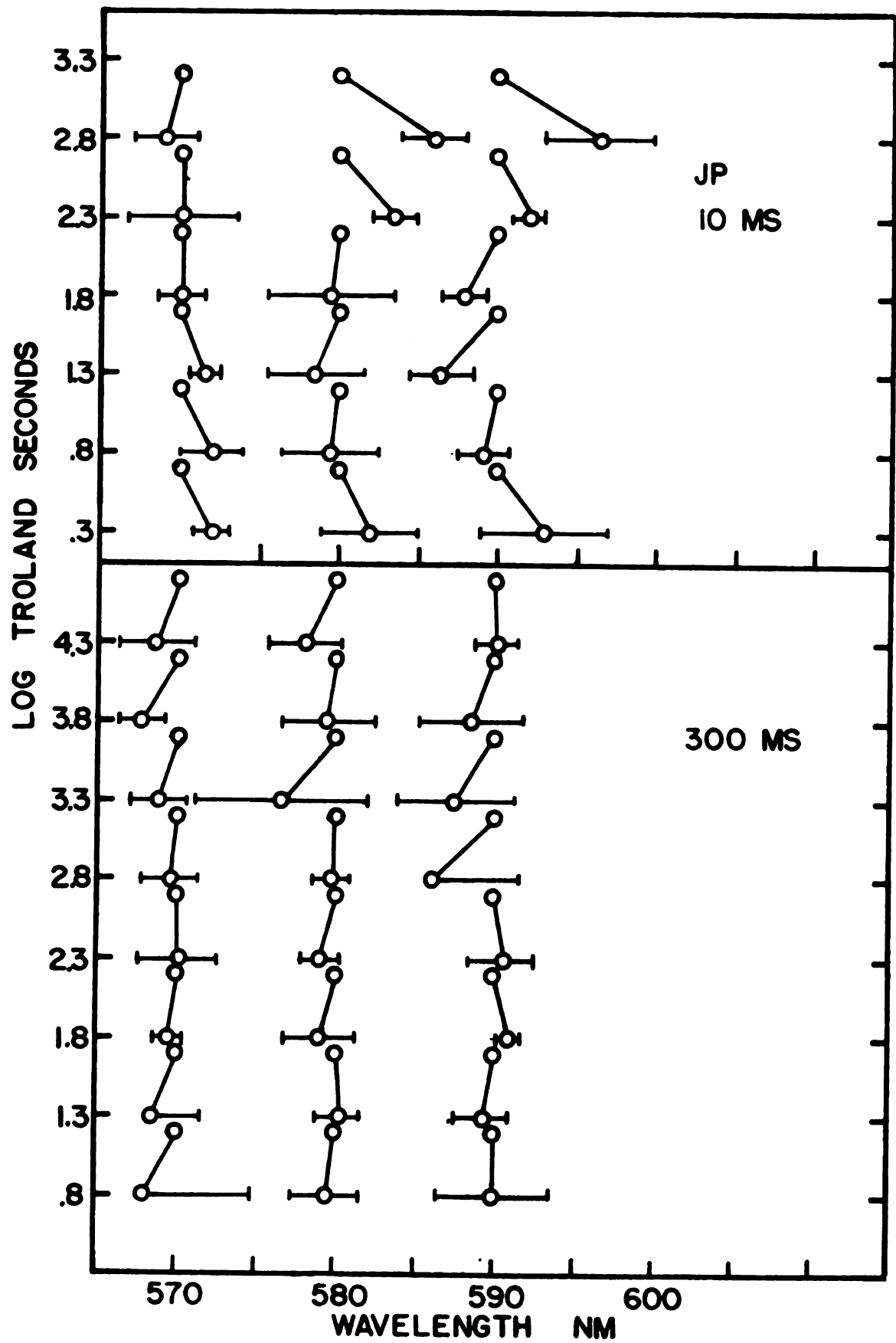


FIGURE 11

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the slopes again become negative. In the long duration data this pattern is not nearly as prevalent. Generally, the slopes in a set of segments are either all positive or all negative in going from low to high intensity.

The method by which smooth constant hue curves were constructed for these data is shown in Figure 12. In essence, the slope of each line segment was taken as an estimate of the slope of the line of constant hue at that intensity. Arbitrarily a point at a luminosity of 1.7 log troland seconds was anchored at its actual wavelength value, for short duration data. For long duration data, the point at 3.2 log troland seconds was anchored at its actual value. These are actually equivalent luminances. The difference in the troland second value is due to the difference in duration. The rest of the line segments were slid along the wavelength axis in the right direction to form a smooth curve.

The smooth curves constructed in this manner are shown as solid curves in Figures 13, 14, and 15. The axes are identical to those in the line segment figures. Again, compare each curve at short and long durations. At short duration the curves tend to have a non-monotonic S shape similar to the curves from Savoie's data shown in Figure 3. At long duration the curves become more nearly monotonic and more closely resemble the data from Purdy's study. The presence of an invariant yellow might also be inferred here as in the Purdy data. One exception does occur here in Figure 13. The long duration curves exhibit a large fall-off toward long wavelengths at low intensities which is not characteristic of Purdy's curves. Perhaps these shifts are still apparent

Figure 12,--Illustration of the method of construction of the smooth lines of constant hue from the hue matches. The end of one line segment was anchored at the standard wavelength and the other line segments were slid along the horizontal axis to form a smooth curve.

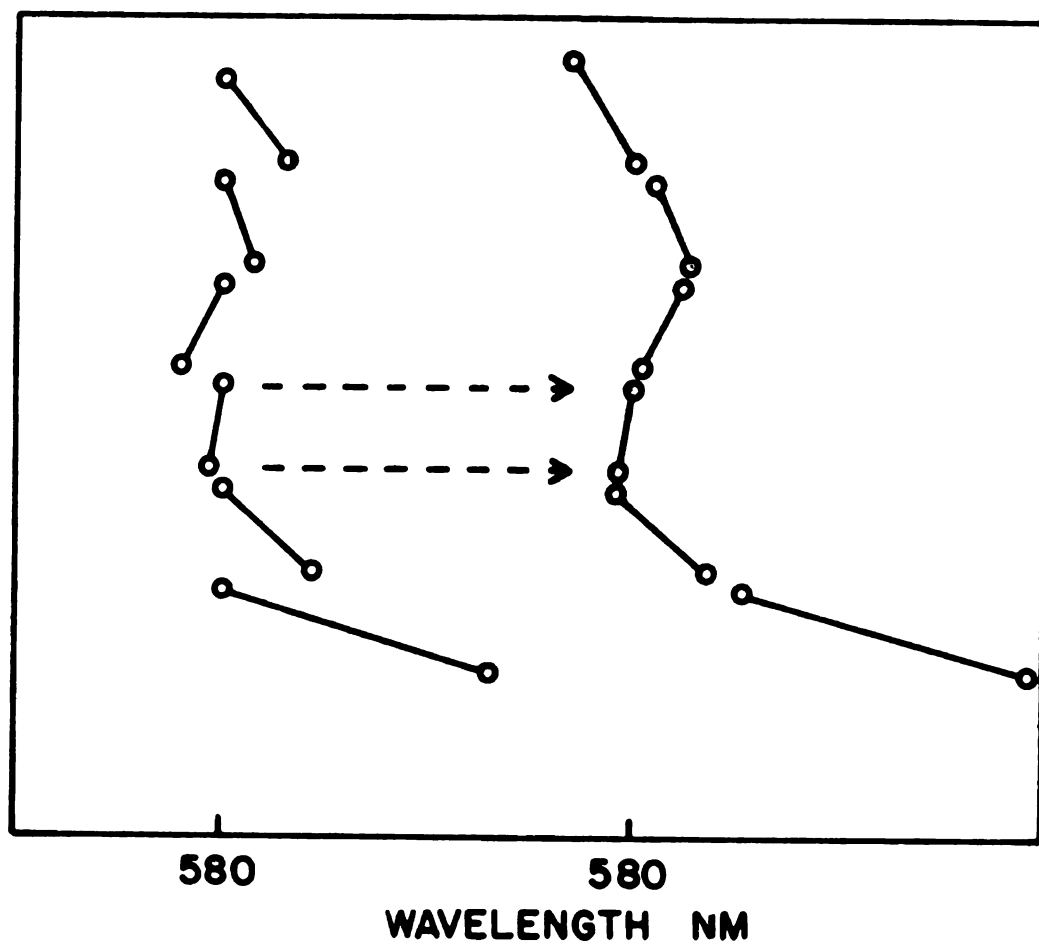


FIGURE 12



Figure 13.--Smooth lines of constant hue in a wavelength-intensity space. Solid lines constructed from the hue matches of Observer AN. The dashed line is the unique yellow curve from Figure 8 for Observer AN. The data in the upper panel were collected with a stimulus duration of 10 msec. and those in the lower panel at 300 msec. Compare the upper panel with the Savoie data in Figure 3 and the lower panel with the Purdy data in Figure 1.

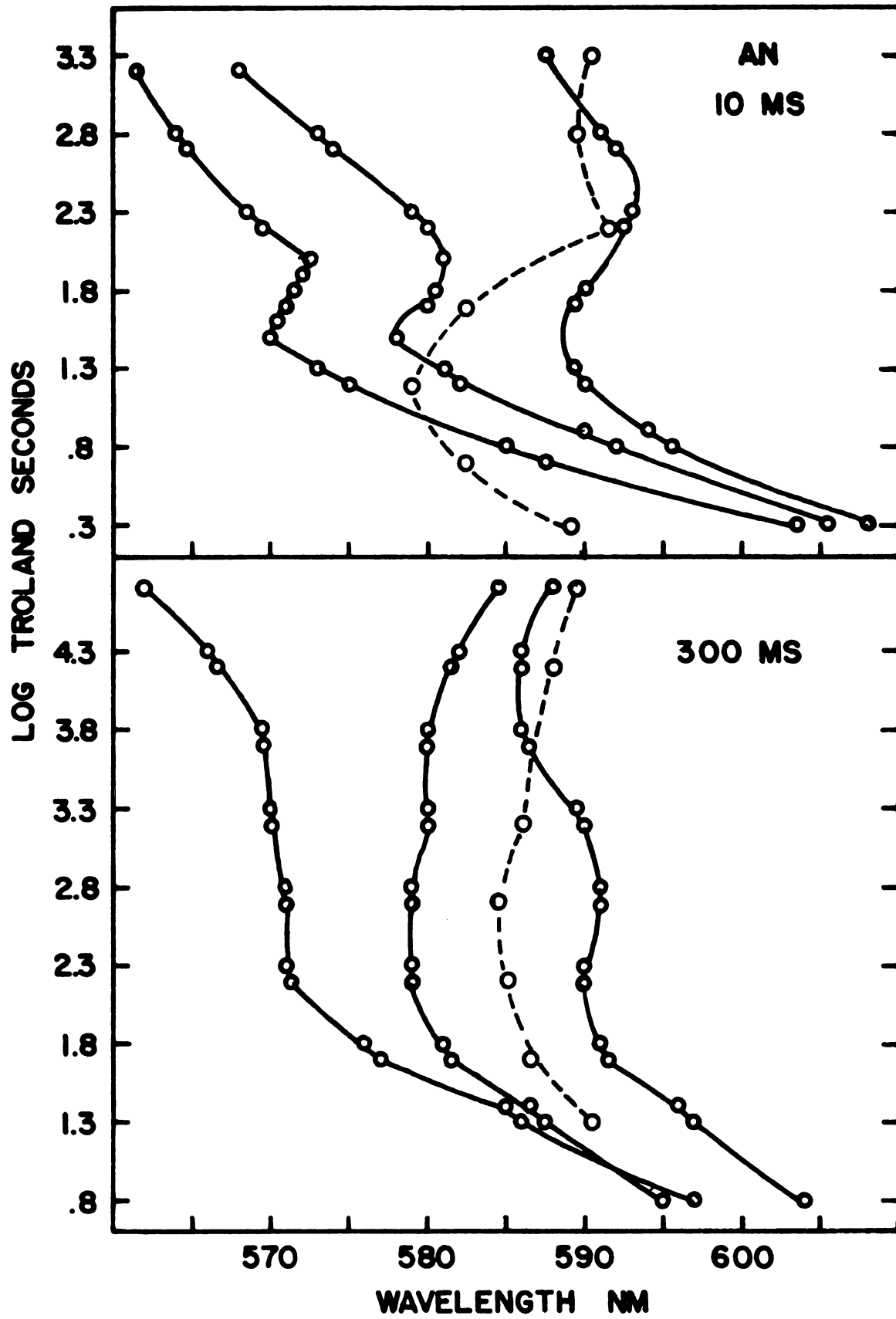


FIGURE 13

Figure 14.--Smooth lines of constant hue in a wavelength-intensity space. Solid lines were constructed from the hue matches of Observer DU. The dashed lines are the unique yellow curves for DU from Figure 8. The data in the upper panel were collected with a stimulus duration of 10 msec. and those in the lower panel at 300 msec. Compare the upper panel with the Savoie data in Figure 3 and the lower panel with the Purdy data in Figure 1.

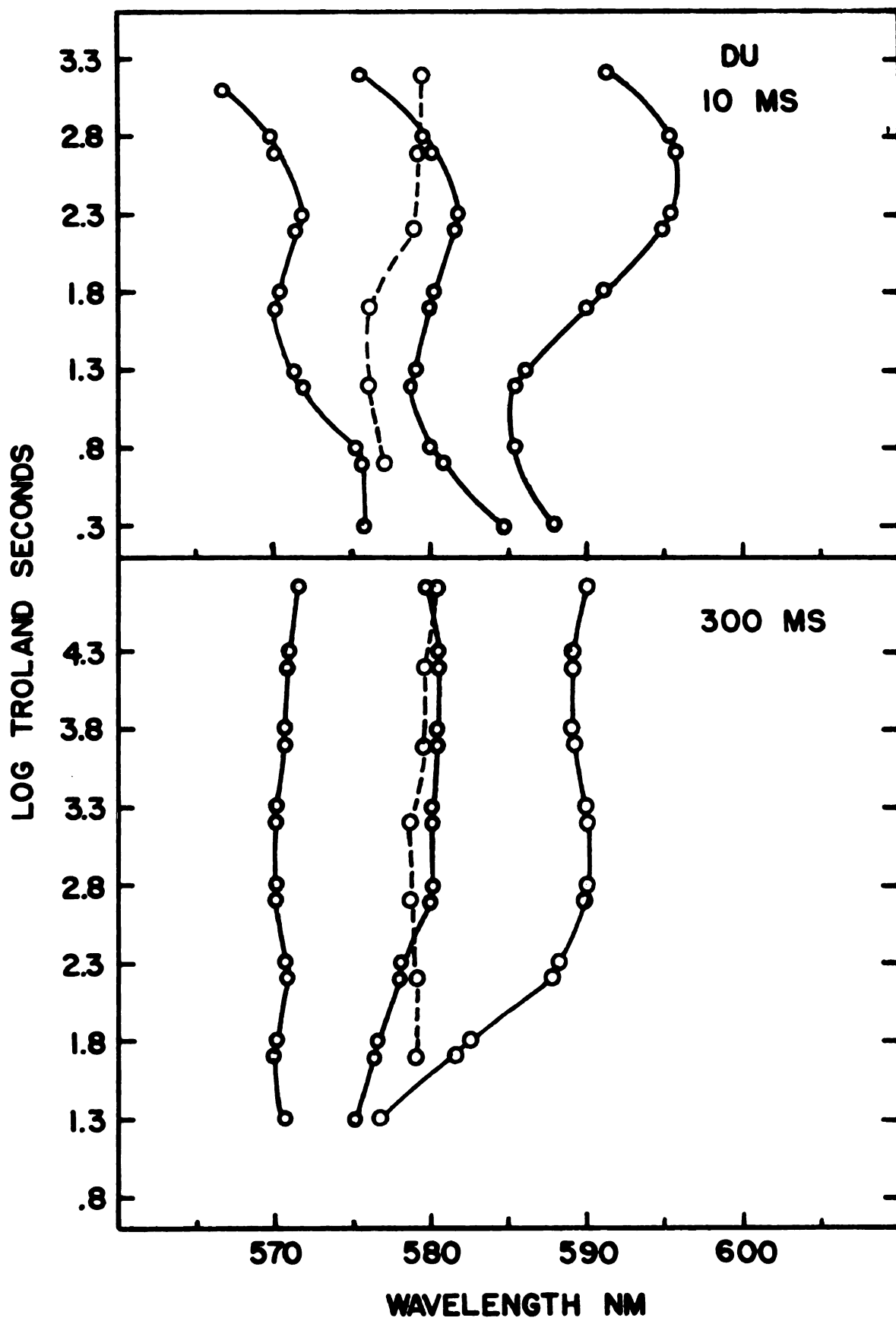


FIGURE 14

Figure 15.--Smooth lines of constant hue in a wavelength-intensity space. Solid lines were constructed from the hue matches of Observer JP. The dashed lines are the unique yellow curves for JP from Figure 8. The data in the upper panel were collected with a stimulus duration of 10 msec. and those in the lower panel at 300 msec. Compare the upper panel with the Savoie data in Figure 3 and the lower panel with the Purdy data in Figure 1.

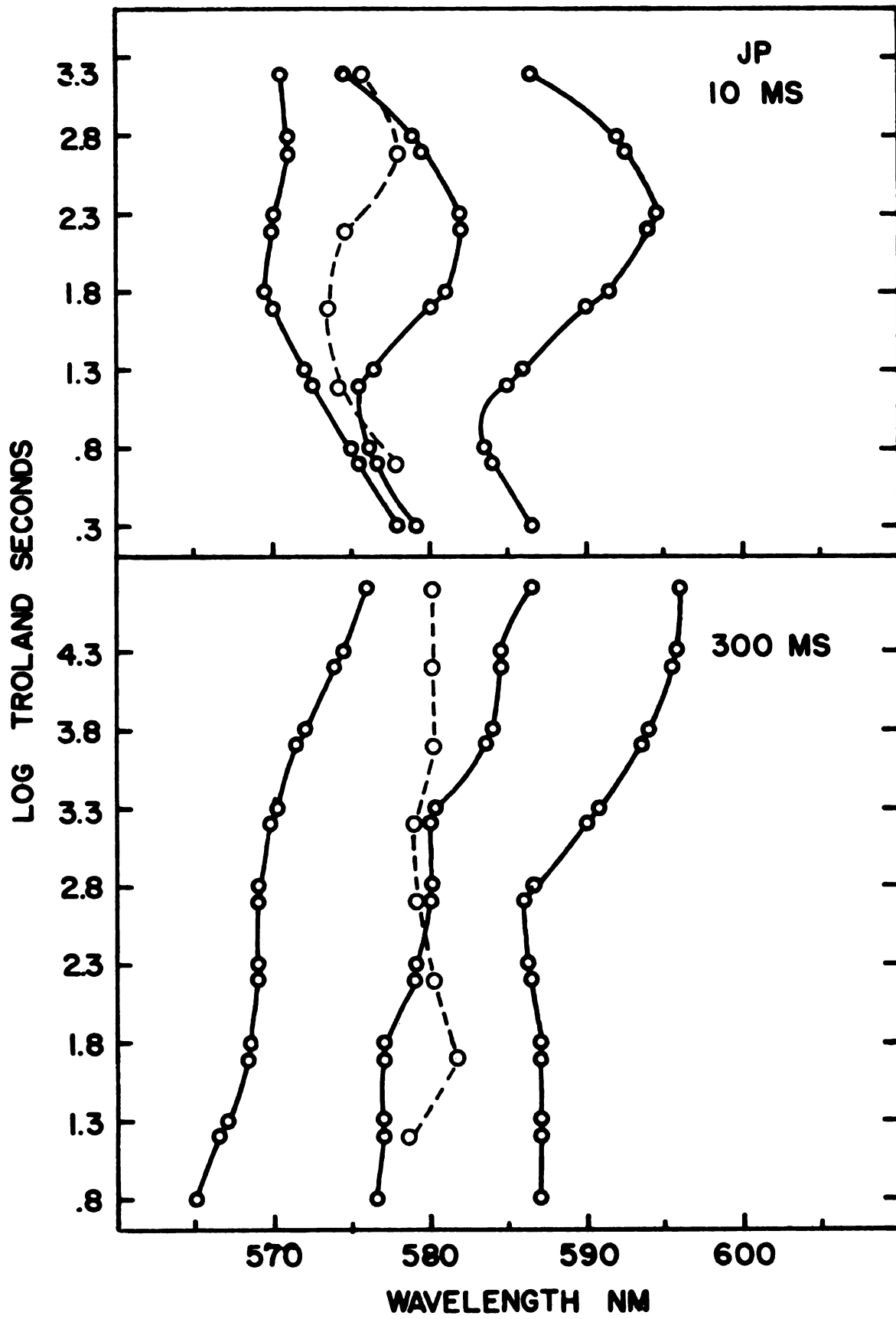


FIGURE 15

because of the low stimulus intensity and the fact that these stimuli are still relatively short in duration compared to Purdy's.

The dashed curves shown in each figure are the curves for unique yellow taken from Figure 8. The point here is to compare the methods at each duration. Qualitatively, the unique yellow curves are similar in shape to the corresponding matching curves. The short duration unique yellow curves are more similar to short duration matching curves than to long duration unique yellow curves. Long duration unique yellow curves are more similar to long duration matching curves than short duration unique yellow curves. It appears, however, that the two methods do not produce data that agree quantitatively. For example, in Figure 13, at short duration the unique yellow curve and the matching curve anchored at 590 nm. almost coincide at a luminance of 2.4 log troland seconds. At a luminance of 1.3 log troland seconds, however, the two curves are separated by 10nm. Since each of the curves is a line of constant hue, if they coincide at one point they should coincide everywhere along their extent.

Since the construction of smooth curves from the matching data involves some addition of errors, another type of comparison was done to eliminate this problem. It is shown in Figure 16. The data from the judgment of unique yellow was used to construct line segments similar to those obtained in the matching procedure. These are shown as solid line segments in the figure. A weighted average of the slopes of the line segments of the corresponding matching data was used to estimate the slope of the line segment whose upper end point corresponded to the upper end point of the segment derived from the unique yellow data. The line segments estimated from the matching data are shown as dashed



Figure 16.--Comparison of the data from the two psychophysical procedures. Line segments connect points of equal hue. Solid line segments are derived from the judgment of unique yellow and dashed line segments are derived from the matching data. Data for all three observers are shown at both short (upper panel) and long (lower) panel stimulus durations.

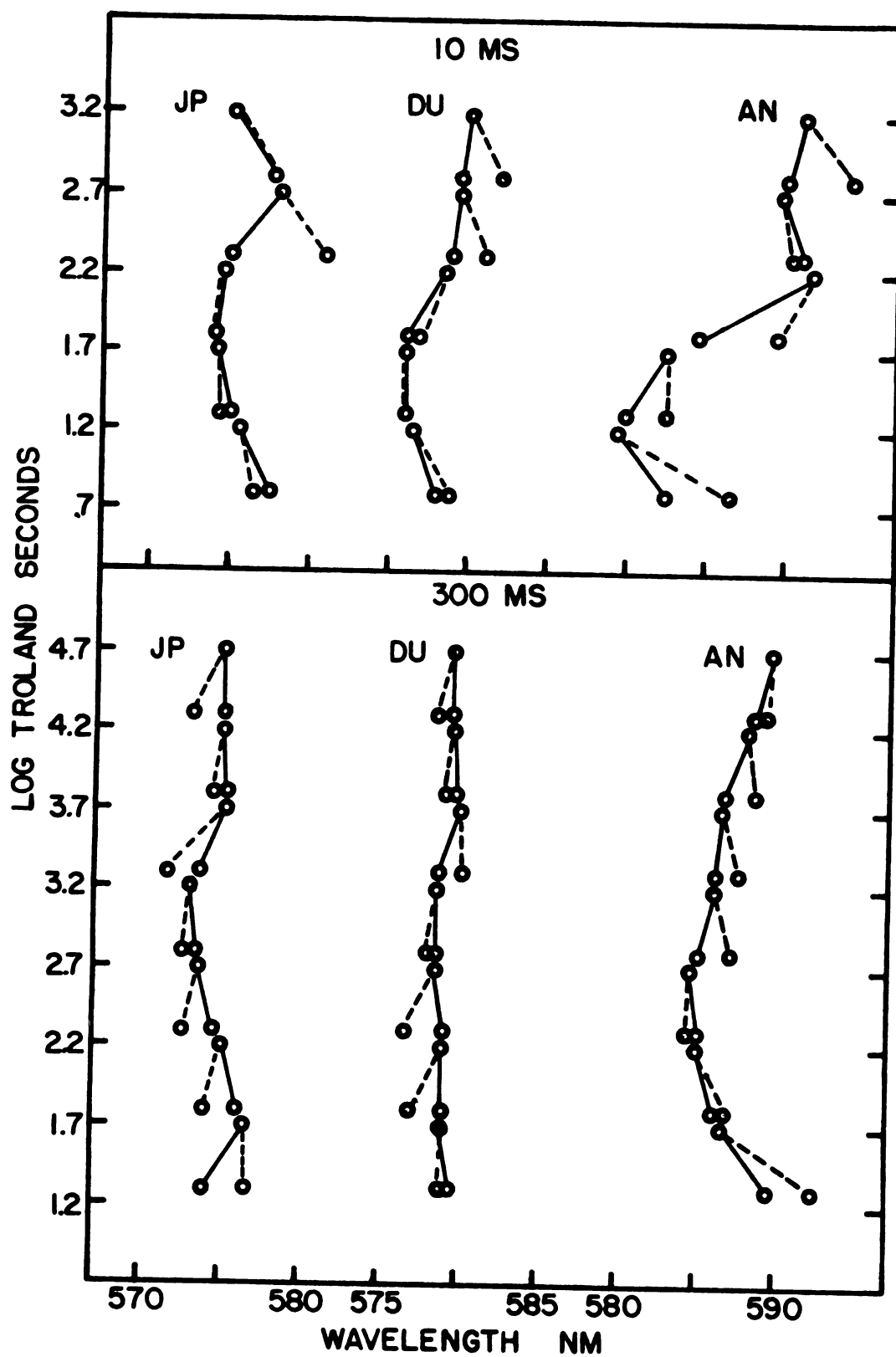


FIGURE 16

line segments in the figure. Some disagreement is still evident, though, in general, the direction of the slopes tend to agree.

The individual differences in observers appear to hold up across methods. For example, Observer JP comes closest to exhibiting an invariant hue (e.g., a straight vertical line) at short duration in the judgment of unique yellow data in Figure 15. His matching curve at 570 nm., short duration, also approaches being a straight vertical line more closely than any of the other short duration matching curves. That is, Observer JP comes closer to having an invariant hue in both methods than the other observers.

DISCUSSION

The results demonstrate that stimulus duration is more important to the differences between the Savoie and Krantz studies than the particular type of judgment demanded of the observer. At identical stimulus durations, the two methods produce qualitatively similar results. This result agrees with the conclusions of Boynton and Gordon (1965), that different methods produce similar results for measurements of the hue shifts.

Quantitative agreement between the two methods is in some cases rather poor at the short duration. Agreement is somewhat better at long duration. The major disagreement appears to occur at high luminances. The unique yellow curves do not appear to bend toward short wavelengths as much as the matching curves. This is shown most clearly in the line segment comparison of Figure 16.

Two factors inherent in the method used here bear further examination. First, a fixation point was used here in both methods. Jameson and Hurvich (1967) have shown that a fixation point can have a

significant biasing effect upon results. It might be argued that a fixation point would have different effects upon the matching and unique yellow judgments, since in the unique yellow judgment the "standard" was an internalized conception of unique yellow. Thus, it might be argued that the fixation point would exert an effect only on the "comparison" stimulus in the unique yellow judgment, while both standard and comparison would be equally affected in the matching procedure. A simple experiment to determine the influence of the fixation point would be useful here.

The second point to be made is that two stimuli are presented in close proximity in the matching procedure, while only one stimulus is presented in the judgment of unique yellow. Thus it is likely that the matching data are confounded by the effects of lateral interactions (see Ratliff, 1965) between the stimuli, while the unique yellow data are not. Experimentation on this problem would also be useful. Effects like these could very well produce quantitative differences of the kind found here.

Despite the quantitative disagreement, the results suggest that stimulus duration is largely responsible for the qualitative differences in monotonicity and occurrence of an invariant hue. Consider the implications of these data in the light of the theoretical analysis given earlier. The data suggest that, at short durations, there is no invariant hue for two of the three observers. These individual differences appear to be reliable. Assuming the opponent-process model described earlier, we must conclude that for observers showing no invariant hue, the functions describing the cone system inputs to the opponent-mechanisms are not of the same shape. Furthermore, the

non-monotonicities of the hue shifts with intensity changes implies that the cone system inputs to the red-green mechanism are a non-linear function of the stimulus intensity.

At long durations the data are more nearly consistent with those of Purdy and Krantz, and hence are more nearly consistent with linear cone inputs to the red-green mechanism.

These results, of course, raise the question: "Why is duration important?" "Which duration yields data which are conceptually easier to interpret?" On the one hand, transient stimuli produce complex responses which are less amenable to analysis than steady-state conditions. On the other hand, steady-state stimuli produce significant changes in the state of adaptation in as short as 100 msec. (see Dowling, 1967; Crawford, 1947; Baker, 1963; and Boynton, et al., 1954), requiring an adequate model of adaption as part of a model of steady-state conditions. Also, during long flashes each eye movement would produce transient effects as the image is swept across the retina. The choice of the simple stimulus will thus depend, ultimately, on the theoretical context within which the data are to be considered.

It is difficult to explain the finding that observers don't have invariant hues at short duration in terms of the opponent-process model presented by Krantz and Hurvich and Jameson. Whether one accepts the adaptation hypothesis or the transient hypothesis, an explanation for the short duration data is much simpler if one concludes that response is non-linear with intensity in the cone mechanisms at short duration.

EXPERIMENT II

In recent years the response-intensity problem has also been considered in the study of visual adaptation. The decrease in sensitivity

of the visual system with increasing levels of background light has long been known. For many years it was thought that the decrease in sensitivity was due to the fact that some of the visual pigment in the receptors was bleached away by the background light thus reducing the expected number of quanta absorbed from a test light. A reduction of the sensitivity by a factor of two was thought to reflect a reduction in the amount of unbleached photopigment by a factor of two (see Hecht, 1937). Campbell and Rushton (1955), however, were able to make measurements of the amount of bleached pigment in the receptors which showed that the change in quantum efficiency produced by bleaching could not in itself account for the change in sensitivity. Rushton (1965) has shown that a background so weak that only 1% of the rods catch a single quantum raises the threshold by a factor of three.

Two very different types of models have been proposed to explain the decrease in sensitivity with light adaptation. One characterizes the change in sensitivity as a passive process which occurs as a consequence of the response-intensity function being a response compression. That is, the increase in response produced by a fixed increment in intensity is smaller when the increment is added to a high intensity than when added to a lower intensity.

The other type of model describes light adaptation as an active process in which inhibitory neural loops change the gain of the visual system in accord with the intensity of the adapting light, analogous to the manner in which a volume knob can be turned to change the gain of a radio. The two models predict different effects of light adaptation

on the Bezold-Brucke Hue shifts. Experiment II was done to differentiate between these two kinds of models.

THE RESPONSE COMPRESSION MODEL.

Using a simplified set of experimental conditions, Cornsweet and Pinsker (1965) asked an observer to discriminate between two simultaneously presented short flashes of slightly different luminance. They found that a just detectable increment in luminance is a fixed proportion of the base luminance over a five log unit range. Such a proportionality rule suggests that the visual system acts as if it extracts the ratio of the signals from the test stimuli. Whenever the ratio exceeds some threshold value, the difference between the flashes is detected. Cornsweet and Pinsker assume that under the conditions of their experiment, dark-adapted with stimuli presented as short flashes, the threshold value of the ratio remained the same. They propose a response compression model to account for their results. First, assume a neural circuit which extracts the algebraic difference between the signals from the test stimuli. Such a differencing mechanism has been found to be a common occurrence in the visual system (e.g., Hartline and Ratliff, 1957) although a mechanism that extracts ratios has not been demonstrated. A differencing mechanism would, however, produce Cornsweet and Pinsker's results if the signals from the test stimuli are logarithmically related to luminance before the difference is taken. If the ratio of the test stimulus luminances were held constant as overall intensity was varied, then the difference between the logarithmic signals the flashes generate would be constant. Whenever the difference exceeds some constant threshold value, the difference between the flashes would be detected. Thus, the fixed-proportion rule would result.

The important point here is that the change in sensitivity of the visual system with increasing levels of light is due to the nature of the response function.

Recently, Boynton and Whitten (1970) have provided some electrophysiological evidence in support of the response compression model of adaptation. They recorded the late receptor potential (LRP) response to test stimuli presented to the macula of Macaque monkeys. There is evidence to suggest that the LRP is the potential transmitted along the receptors and involved in activation of second-order cells (Brown and Murakami, 1967; Brown, 1968). The response to a test flash of varying intensity was described by the equation:

$$R_t = \frac{I_t^n}{I_t^n + K_r} \quad \text{Equation I}$$

where R_t is response magnitude.

I_t is the test flash intensity.

n is an exponent of .73 determined from data.

K_r is the saturation constant of 831 trolands determined from the data.

This is a response compression function similar to the log function deduced in the Cornsweet and Pinsker model.

When the test stimuli were superimposed on an adapting field the intensity of the test flash needed to produce a criterion response increased with the intensity of the background. Boynton and Whitten propose that the fundamental reason why the presence of a background reduces the response to an incremental flash is that it "produces a steady receptor response to which the incremental response must add. The non-linearity expressed by Equation I, reflecting a power law

response and the effects of saturating the receptor potential, produces a response compression which progressively reduces the effectiveness of a given incremental flash as the responses to the adapting field become larger."* Thus, the response to background plus test flash is described by the equation:

$$R_{t+a} = \frac{(I_a + I_t)^n}{(I_a + I_t)^n + K_r}$$

where R_{t+a} is the response to a test flash on a background.

I_a is the background luminance.

I_t , n , and K_r as above.

The Boynton and Whitten model is, in general, a passive model of adaptation similar to the Cornsweet and Pinsker model. The change in sensitivity with increasing background level is due to the fact that the function relating response to intensity is a response compression.

THE SCALAR GAIN CONTROL MODELS.

Barlow and Sparrock describe a compelling demonstration of the existence of a gain control type of adaptive mechanism (1964). If the image of a small disk of light is stabilized on the retina it rapidly fades to a dim grey patch. If the observer now superimposes the disk on a large unstabilized background, the area of the background over which the stabilized image is projected appears to be dimmer than the rest of the background. The result is unexpected since this area is actually the most intense, consisting of illumination from both the background and the stabilized disk of light. Presumably, the gain of the area of the retina upon which the stabilized image falls has been turned down by the active mechanism of light adaptation. This is

* Boynton, R., & Whitten, D., 1970, pg. 1424.

reflected in the fact that the brightness of the stabilized image fades. The gain is presumably turned down so much in this area that the combined luminance of the background and the stabilized disk produces a smaller response than the background alone presented to an unadapted area.

In general, gain control models of adaptation suggest that the gain of the visual system is controlled by feedback or feed-forward neural loops. Adaptation is thus an active process in which the system changes itself in order to operate effectively at a given level of light adaptation. [There are also accompanying changes in spatial and temporal properties of the system (Barlow, 1972).] Rushton (1972) has proposed a scalar gain control model in which response is rescaled in accord with the magnitude of the adapting signal. This general type of model might be described by the equation:

$$R_t = [F(I_t)] \frac{K}{K + A(I_a)}$$

where R_t is the response to a test flash.

$F(I)$ is the function describing the relationship between response and intensity.

$A(I_a)$ is the function describing the relation between the signal which operates the gain control mechanism and the adapting intensity.

K is a constant which represents receptor noise or the dark light.

I_a and I_t are the background and test flash luminances, respectively.

According to this formulation, the presence of a fixed background reduces the signal produced by any test flash by a fixed proportion. As the background is reduced to zero the second term on the right side of the equation reduces to $\frac{K}{K}$, or one. As the background is increased the signal produced by a given test flash is reduced by a greater proportion.

THE PROBLEM.

A choice between the two classes of models described above can be made by observing effects of light adaptation on the Bezold-Brucke Hue Shifts. First, assume a general opponent process model of hue coding described by the equation:

$$\text{Hue} = \frac{a[F_{\alpha}(I_{\alpha})] - b[F_{\beta}(I_{\beta})] + c[F_{\gamma}(I_{\gamma})]}{d[F_{\alpha}(I_{\alpha})] + e[F_{\beta}(I_{\beta})] - f[F_{\gamma}(I_{\gamma})]} \quad \text{Equation 4}$$

where a,b,c,d,e,f are constant weighting factors, and

$F_{\alpha}(I_{\alpha})$, $F_{\beta}(I_{\beta})$, $F_{\gamma}(I_{\gamma})$ are non-linear functions describing response as a function of quanta absorbed, I, in the short, middle, and long wavelength cone systems (see Experiment I).

This is a general form of the Hurvich-Jameson opponent process model described in Experiment I. The numerator and denominator of the term on the right represent the linear combination of the cone system inputs to the red-green and blue-yellow opponent systems, respectively. Hue is a function of the ratio of the activities in the blue-yellow and red-green systems. Assume, also, that adaptation occurs independently within each of the cone systems. At least to a first approximation the cone systems appear to operate independently (see Stiles, 1946; Alpern, 1965; Alpern and Rushton, 1965; and DuCroz and Rushton, 1966) since a

threshold determined by a given cone system appears to be affected by adaptation within that system alone.

Consider the effect of superimposing the hue stimuli on a white background as predicted by the response compression model. The effect of the background is to produce a steady response to which the incremental response must add. Thus the response to a hue stimulus plus the background in each cone system is described by $F(I_a + I_t)$, where I_a represents quanta absorbed from the background and I_t , quanta absorbed from the hue stimulus. The function, F , describes the relation between response and quanta absorbed. If the nature of the functions, F , were known, then it would be a simple matter to add the quanta absorbed from the background into each function and predict the hue of a stimulus superimposed on the background. Since the nature of the functions is not known (see Experiment I), an indirect route must be taken.

A white stimulus is theoretically defined as producing zero activity in both the red-green and blue-yellow opponent mechanisms. The definition follows the opponent-process model of Hurvich and Jameson. At present, there appears to be no empirical evidence on this problem. White could be some other combination of activities in the opponent systems. This is probably the weakest of the assumptions. Conceivably, there are other models that could be used with a different definition of white to predict the effects of light adaptation. If the white background produces no activity in opponent color mechanisms, the values of the numerator and denominator of Equation 4 are determined entirely by the hue stimulus. The effect of the background is to raise the response to the hue stimulus to a higher level on the response function of each cone system. Since the functions are non-linear the hue of the stimulus

will be equivalent to that of a stimulus of the same wavelength but higher intensity when the background is not present. The predicted effect of the background on the lines of constant hue is shown in Figure 17. The solid line represents a dark-adapted line of constant hue and the dashed line represents a line of constant hue determined in the presence of the white background. Log intensity of the hue stimulus is plotted along the ordinate and wavelength along the abscissa. Since the background has the effect of adding a constant amount of intensity to the hue stimuli, the lines of constant hue should be shifted downward without change of shape on a linear plot. However, on the logarithmic intensity scale used here, the effect will be to shift the lower portion of the curve a greater distance downward than the upper portion. This change of shape is due entirely to the nature of the log transformation. The predicted curve (in Figure 17) was actually produced by subtracting a constant from the intensity of the stimuli used to plot the dark-adapted curve and then plotting the points on the log intensity scale. This has the desired effect of moving the hue of a high intensity stimulus to a lower stimulus intensity.

Now, consider the predicted effect of light adaptation in terms of the scalar gain control model. Assume, first, that cone signals have already passed through the non-linear function, F , described above, and that they then pass through a scaling mechanism that reduces all incoming signals by a constant proportion $\frac{1}{x}$ as a result of adaptation to background. Since the background is white, assume that the scalar reduction is the same in each cone system. Substituting into Equation 4:

Figure 17.--Predicted transformation of the lines of constant hue on the basis of the response compression model of light adaptation. The lower portion of the constant hue line is shifted downward on the intensity axis as a result of light adaptation.

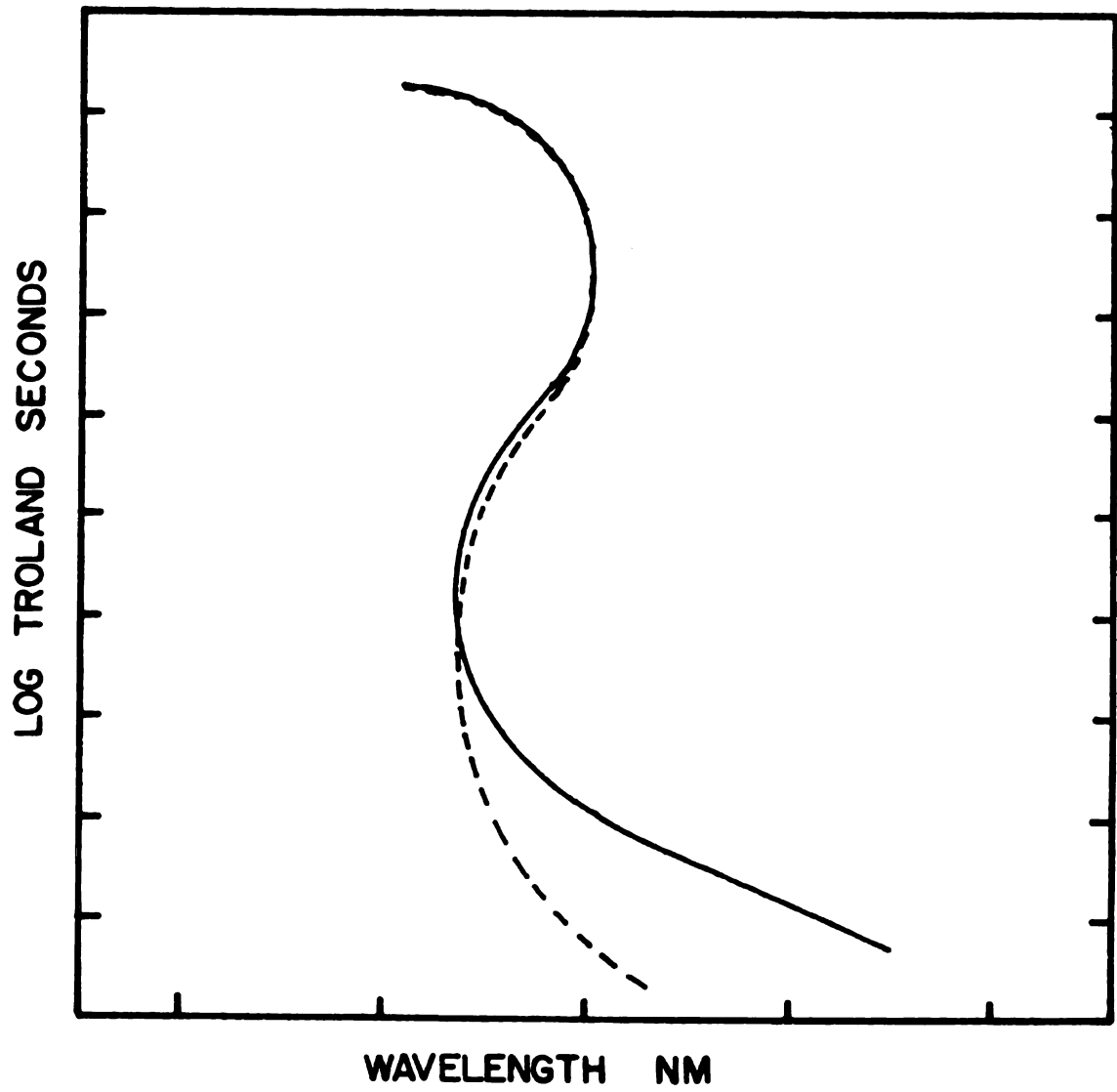


FIGURE 17

$$\text{Hue} = \frac{a[F_{\alpha}(I_{\alpha})] \left(\frac{1}{x}\right) - b[F_{\beta}(I_{\beta})] \left(\frac{1}{x}\right) + c[F_{\gamma}(I_{\gamma})] \left(\frac{1}{x}\right)}{d[F_{\alpha}(I_{\alpha})] \left(\frac{1}{x}\right) + e[F_{\beta}(I_{\beta})] \left(\frac{1}{x}\right) - f[F_{\gamma}(I_{\gamma})] \left(\frac{1}{x}\right)}$$

But the term $\frac{1}{x}$ cancels out and the original equation is left. Thus a scalar mechanism of adaptation after the non-linearity would have no effect on the hue of a stimulus superimposed on a white background. Consequently, Figure 17 also shows the predicted effect of this scalar model.

Consider now, a scalar reduction prior to the non-linearity. Assume that the signal, linearly related to stimulus intensity, passes through a scaling mechanism and then through the non-linear function, F , before being input to the opponent mechanism. Assume the presence of the background again produces a reduction $\frac{1}{x}$ in each cone system. Equation 4 now becomes:

$$\text{Hue} = \frac{a F_{\alpha} [I_{\alpha} \left(\frac{1}{x}\right)] - b F_{\beta} [I_{\beta} \left(\frac{1}{x}\right)] + c F_{\gamma} [I_{\gamma} \left(\frac{1}{x}\right)]}{d F_{\alpha} [I_{\alpha} \left(\frac{1}{x}\right)] + e F_{\beta} [I_{\beta} \left(\frac{1}{x}\right)] - f F_{\gamma} [I_{\gamma} \left(\frac{1}{x}\right)]}$$

This is equivalent to simple reduction of stimulus intensity. Thus the prediction of this model is that lines of constant hue will be shifted upward on the intensity axis as shown in Figure 18, as a result of adaptation to the background.

One of the assumptions in the above analysis is that the background produces equal scaling factors, $\frac{1}{x}$, in each cone system. Consider the effects of unequal scaling factors in the model in which the scalar occurs before the non-linear function. The signal input to the non-linearity in one cone system would be reduced by a consistently smaller or greater proportion than the signal in the other cone system. This is equivalent to changing the wavelength of the stimulus in the dark-adapted state. Thus, the effect of a slight inequality in the

Figure 18,--Predicted transformation of the lines of constant hue on the basis of the gain control model which acts upon a linear signal. The constant hue lines are shifted upward on the intensity axis as a result of light adaptation.

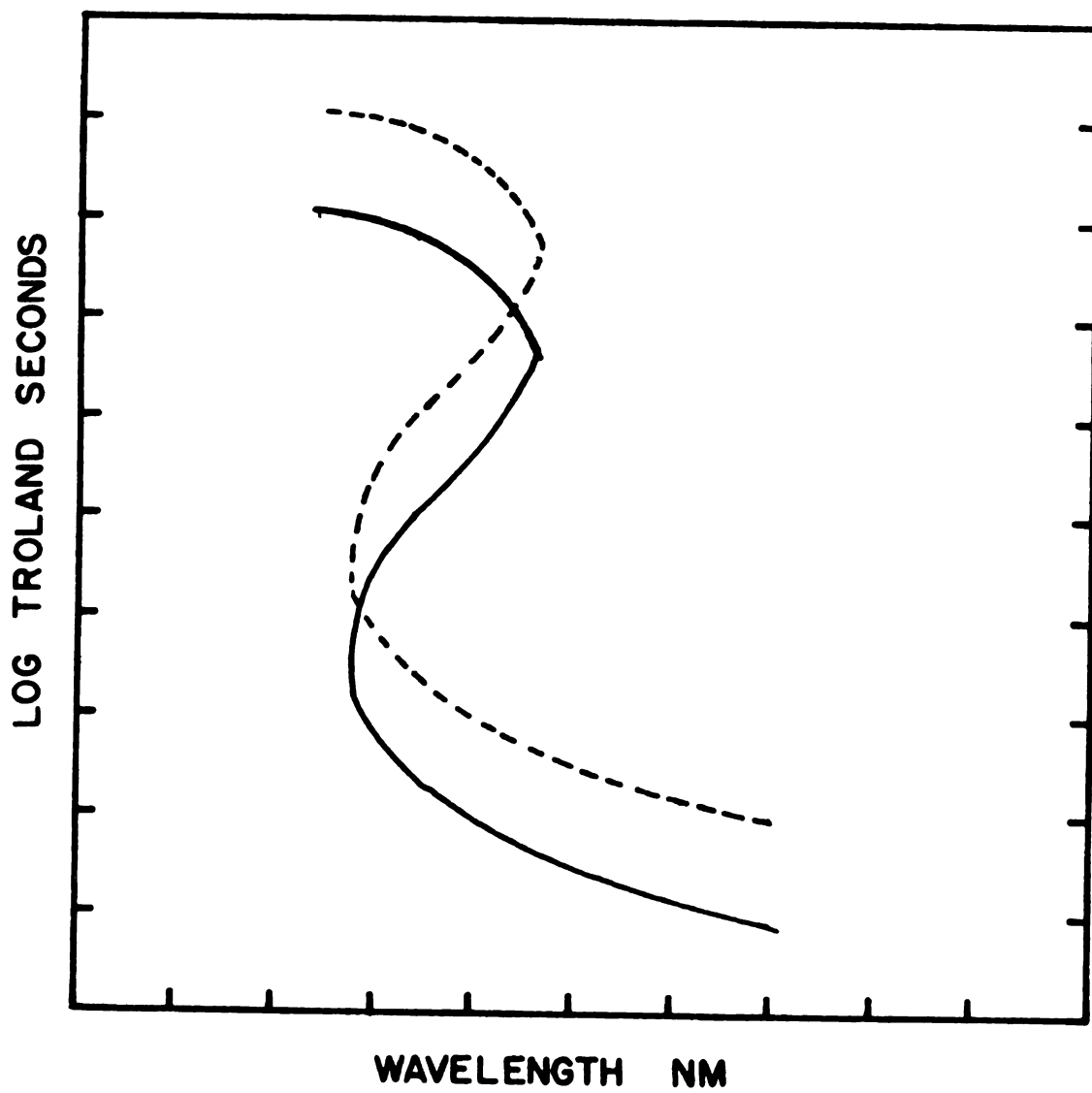


FIGURE 18

scaling factors would be to make the light-adapted lines of constant hue match the shape of dark-adapted lines at a slightly different wavelength, as well as shifting the curves upward on the intensity scale. Small violations of this assumption would not produce drastic effects, since the change in shape of the constant hue lines with wavelength is a rather gradual one.

Inequalities in the level of adaptation of the cone systems in the response compression model would slightly change the shape of the constant hue lines. If the background were only nearly white than a small constant would be added to hue signals produced by the hue stimuli in the opponent mechanisms. The effect of adding a small constant would be larger when the intensity of the hue stimuli was low. As the intensity of the hue stimuli was increased, the effect of the added constants would decrease. Thus the deviation from the shape of the dark-adapted curve would increase with decreasing stimulus intensity. The deviation would be similar to that produced by gradually changing the wavelength of the hue stimuli as the intensity was reduced. This effect would be added to the shift of the curve to lower intensities described earlier.

In the third model, with the scalar gain control after the non-linearity, the effect of unequal scalars would be to add another transformation in the shape of the constant hue lines to the one described in the last paragraph. This transformation could not be matched by any change in wavelength as the earlier transformations were and cannot be described without knowledge of the nature of the response-intensity functions, F .

THE EXPERIMENT.

The design of the experiment was relatively simple in nature. The matching method (Savoie Method) of Experiment I was used to measure the hue shifts, but here the standard and comparison targets were superimposed upon a continuously present background which was perceived as white. A white which meets the requirements of the definition given earlier has not yet been empirically determined though some discussion of this problem can be found in the work of Hurvich and Jameson (1951). Lines of constant hue were constructed as in Experiment I and compared with those constructed from the dark-adapted data of Experiment I. Depending on the location of the non-linearity and whether there is an active scalar mechanism of adaptation in each cone system, the hue shift curves should be transformed in one of the ways described above.

METHODS

The matching procedure and methods used were identical to those used in Experiment I except for the presence of the background upon which the hue stimuli were superimposed. Two levels of background illumination were used: 1.1 and 2.1 log photopic trolands. Neither of these backgrounds produces a significant amount of bleaching (Cornsweet, 1970). At the beginning of each run, the observer viewed the background for at least two minutes in order to achieve a stable level of adaptation. The background was present continuously throughout the run and the observer was instructed to view it continuously in order to maintain the stable adaptive state.

1

Data were collected at each of the standard wavelengths used in Experiment I (570, 580, and 590 nm.), with each level of background illumination. The same stimulus illuminances were used except that some of the lower levels were omitted since they could not be seen in the presence of the background. Stimulus duration was 10 msec. in all cases. Observers JP and AN (the author) participated in this portion of the study. At least four staircases, on two different days, were run at each condition.

APPARATUS.

The optical system described in Experiment I (Figure 5) was used with only one change. The field stop in channel C, which produced the fixation point in Experiment I was removed. In its place a field stop was inserted to provide the 10-degree background field. The fixation point was a small dark spot on a cover slip inserted in the background beam. The field stop and cover slip were inserted so as to be at the same optical distance as the stimuli. The spatial arrangement of the stimuli is shown in Figure 19.

RESULTS

The results show that the lines of constant hue are shifted upward on the intensity axis without change of shape.

Raw data for observers AN and JP are shown in Figures 20 and 21, respectively. Each panel presents results at a given state of adaptation. The data in the upper panel, taken from Experiment I, were collected with the observer dark-adapted. The middle and lower panels show results with white backgrounds of 1.1 and 2.1 log trolands, respectively. Wavelength is scaled along the horizontal axis and test stimulus intensity along the vertical axis in log troland seconds. The

Figure 19.--Schematic diagram of the appearance of the stimuli on a ten degree adapting background.

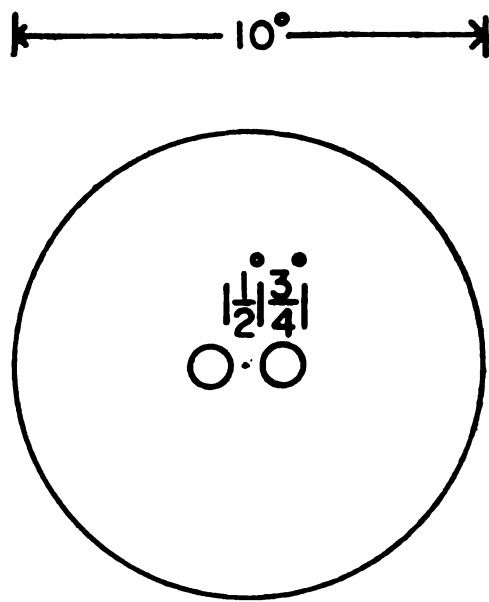


FIGURE 19

Figure 20.--Line segments connecting points of equal hue in a wavelength-intensity space, determined from the hue matches of Observer AN under different conditions of light adaptation. Horizontal lines with vertical hash marks indicate 80% confidence intervals.

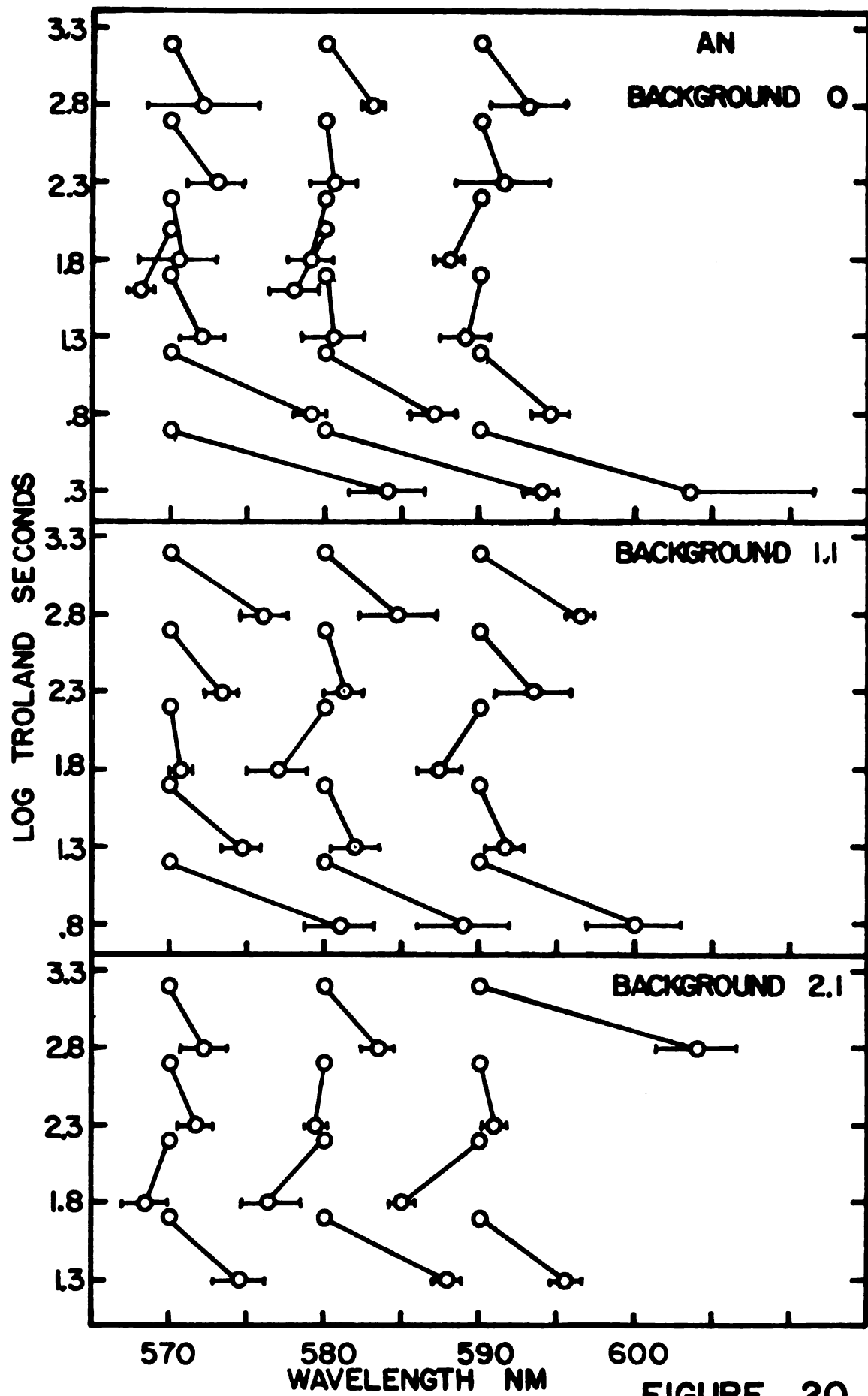


FIGURE 20

Figure 21.---Line segments connecting points of equal hue in a wavelength-intensity space, determined from the hue matches of Observer JP under different conditions of light adaptation. Horizontal lines with vertical hash marks indicate 80% confidence intervals.

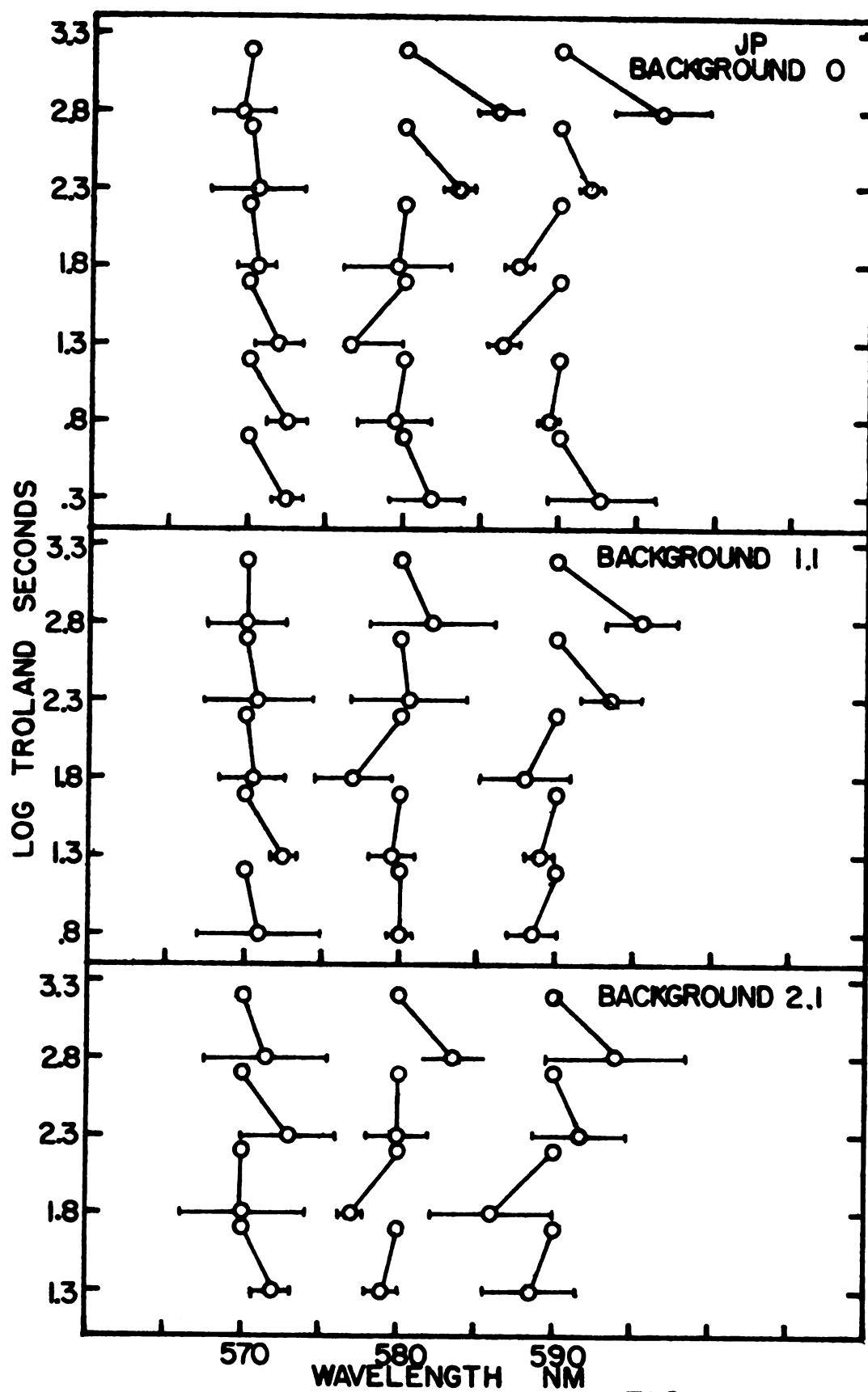


FIGURE 21

horizontal lines with vertical hash marks indicate 80% confidence intervals based on staircase means. The upper end of each line segment is located at the standard wavelength and the lower end is located at the wavelength of the comparison stimulus that matched the standard in hue. Results under light-adapted conditions show the same characteristic pattern that occurs in the dark-adapted data. At low intensities the slopes of the segments are negative; at middle wavelengths, positive; and at high intensities the slopes again become negative.

Smooth curves of constant hue constructed from these data by the method described in Experiment I (see Figure 12) are shown for AN and JP, respectively, in Figures 22 and 23. For direct comparison, the light- and dark-adapted data are superimposed in Figure 24. Data for AN are shown in the upper panel and JP in the lower panel. Axes are as before. The solid curves are dark-adapted data, the dashed curves with adaptation to the low intensity background, and the dotted curves with adaptation to the high intensity background. It is clear that light adaptation to the background does have an effect on the lines of constant hue. They appear to be shifted upward and to the right in the wavelength-intensity space as a result of adaptation to the background. The shape of the curves clearly does not appear to be altered in the manner predicted by the response compression model (see Figure 17). Since the intensity scale is logarithmic, an intact shift of the curves in the vertical direction represents a multiplicative transformation of the sort predicted by the form of the scalar gain control model in which the gain control exerts its effect before the non-linearity (see Figure 18).

Figure 22.--Smooth lines of constant hue in a wavelength-intensity space constructed from the data of Observer AN under different conditions of light adaptation.

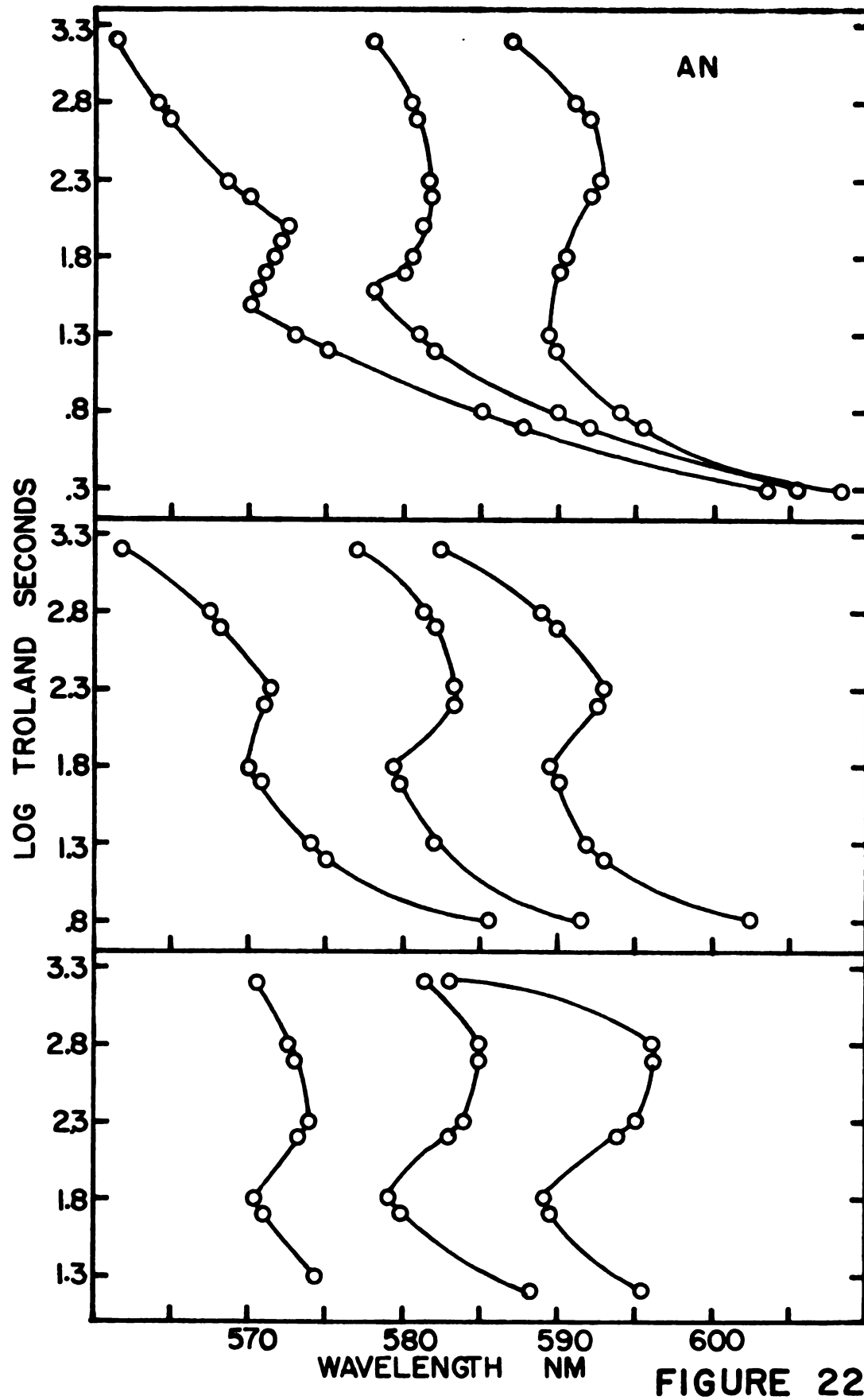


FIGURE 22

Figure 23, -- Smooth lines of constant hue in a wavelength-intensity space constructed from the data of Observer JP under different conditions of light adaptation,

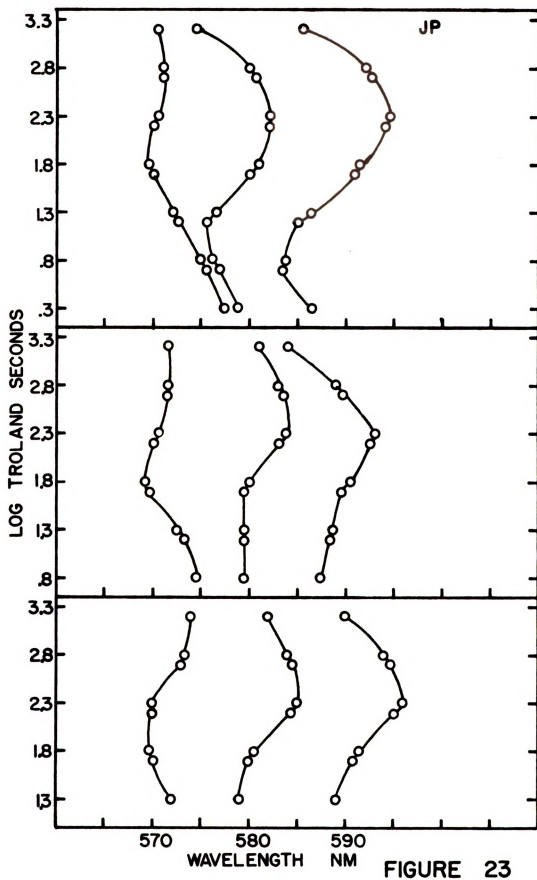


FIGURE 23

Figure 24.--Direct comparison of the lines of constant hue under different conditions of light adaptation for both observers AN and JP. Note that the light-adapted curves appear to be shifted upward and to the right in the wavelength-intensity space.

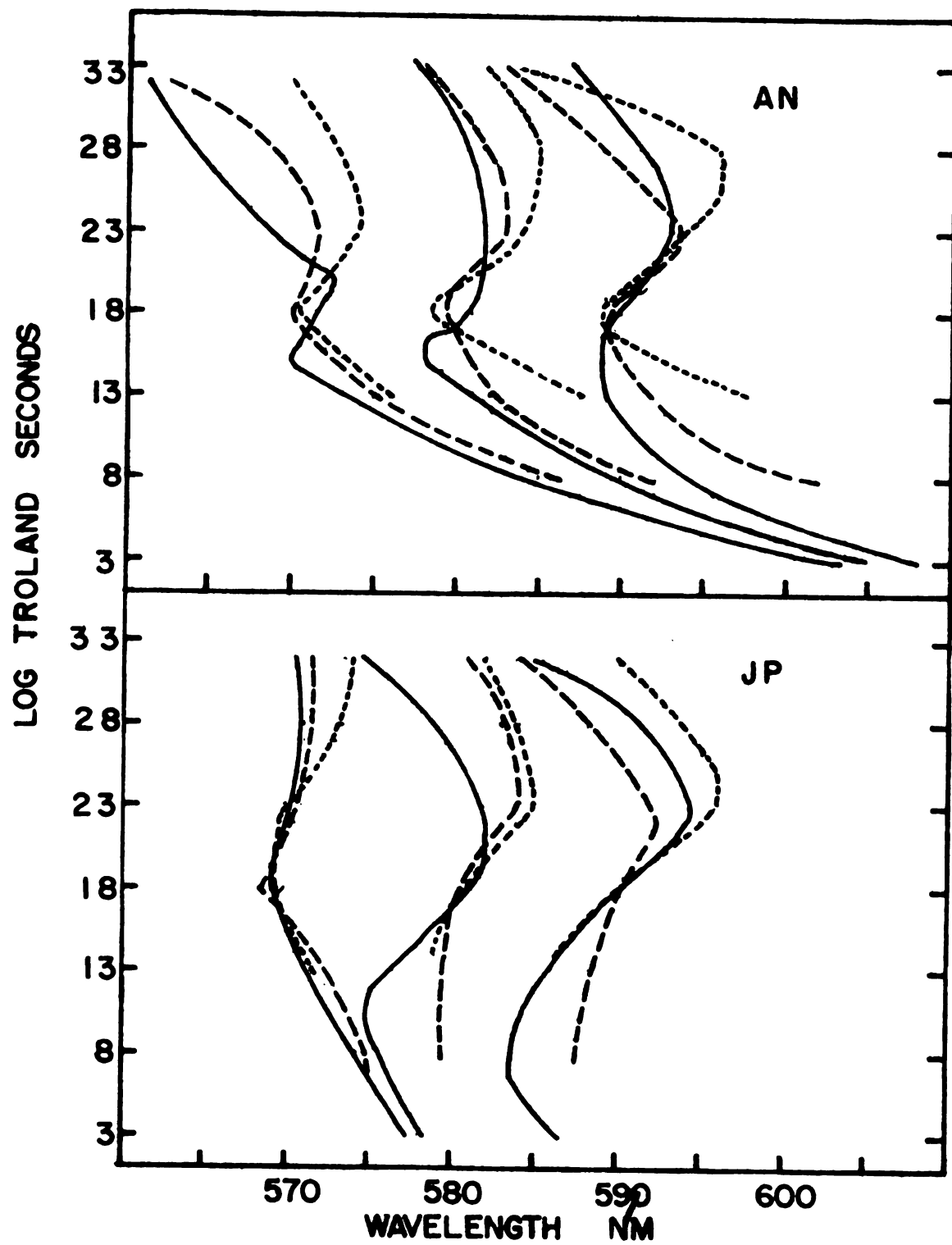


FIGURE 24

Figure 24.--Direct comparison of the lines of constant hue under different conditions of light adaptation for both observers AN and JP. Note that the light-adapted curves appear to be shifted upward and to the right in the wavelength-intensity space.

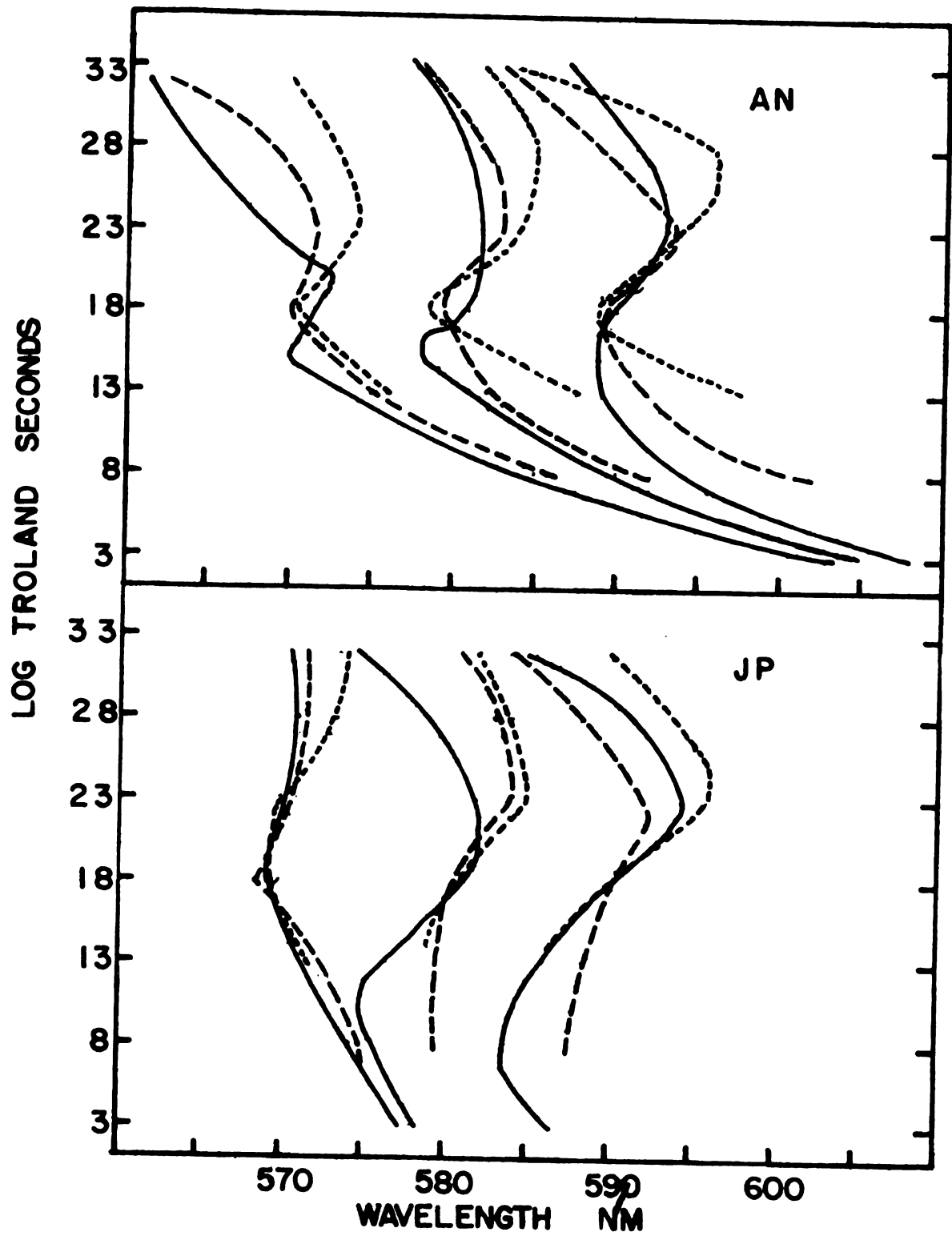


FIGURE 24

The shift to the right is probably due to the manner in which the curves were constructed (see Figure 12). The point on each curve at an intensity of 2.2 log trolands was arbitrarily anchored at the standard wavelength. Sliding the curve up or down along the intensity axis with the additional requirement that the curve must pass through a given wavelength at the intensity of 2.2 log trolands requires that the curve also be shifted along the horizontal axis since the curves are not straight vertical lines.

In Figure 25 the light-adapted curves have been shifted downward and to the left in order to superimpose them over the dark-adapted curves. The data collected with low level adaptation have been shifted down .2 log units and those with high level adaptation, .4 log units. Shifts to the left, of not more than 3 nm., were made arbitrarily in order to bring the light-adapted curves in register with the dark-adapted curves. Deviations in the shape of the light-adapted curves from the dark-adapted curves are generally within the limits of experimental error (see Figure 20 for confidence limits of individual points on the curves) and in most cases do not appear to be systematic. One exception to this rule appears in the curves at 590 nm. The top of each light-adapted curve appears to have a steeper slope than the dark-adapted curve for both subjects. The largest deviations occur out toward the ends of the curves where summation of errors is likely to occur due to the method of construction.

Thresholds for detecting the test stimuli were determined in the dark-adapted state and with the adapting backgrounds using a method of constant stimuli. Adaptation to the backgrounds increased the detection threshold by approximately the same factor that the constant hue lines

Figure 25. ← Lines of constant hue with the light-adapted curves shifted downward and to the left so as to be superimposed over the dark-adapted curves. Note that the shapes of the light- and dark-adapted curves are approximately the same.

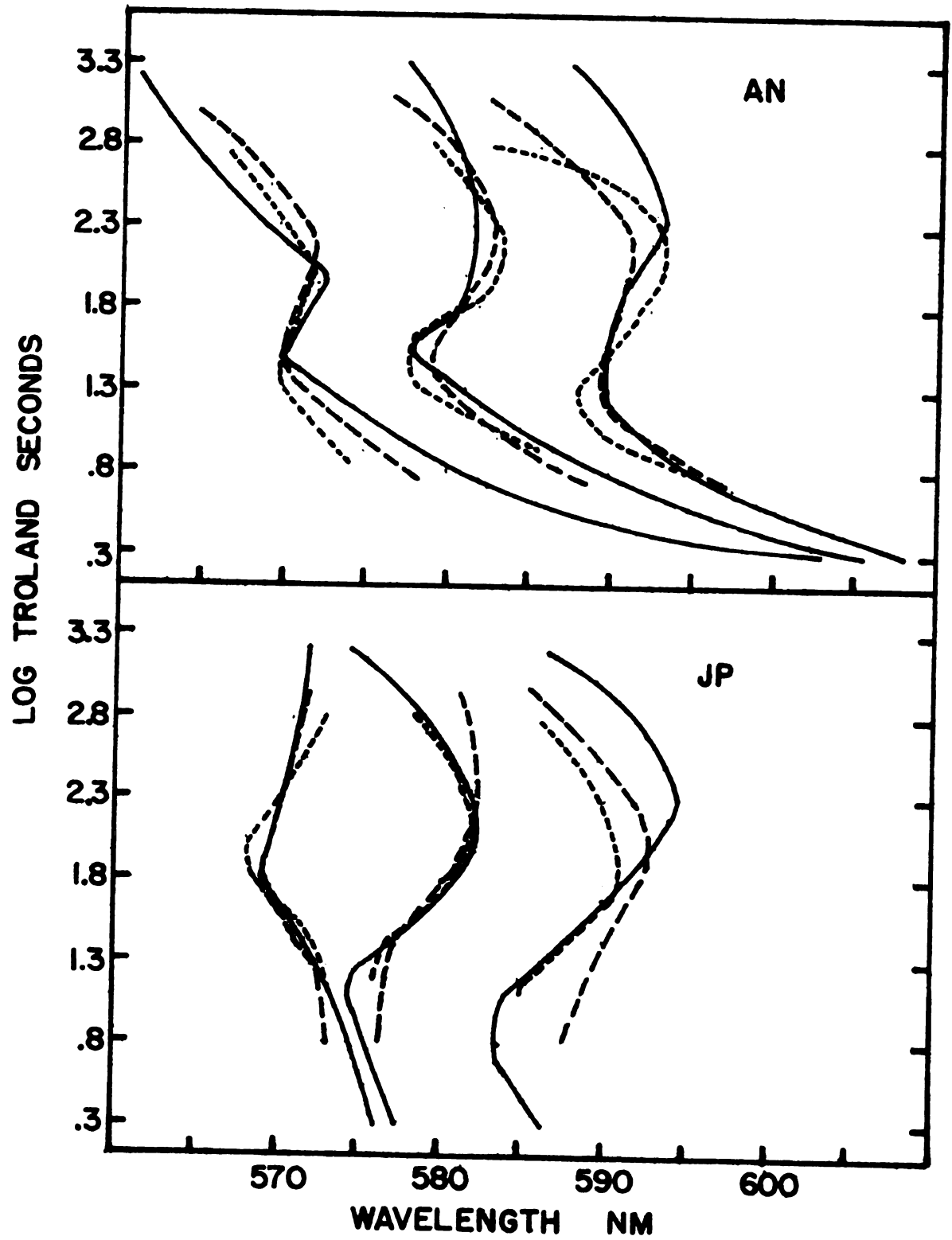


FIGURE 25

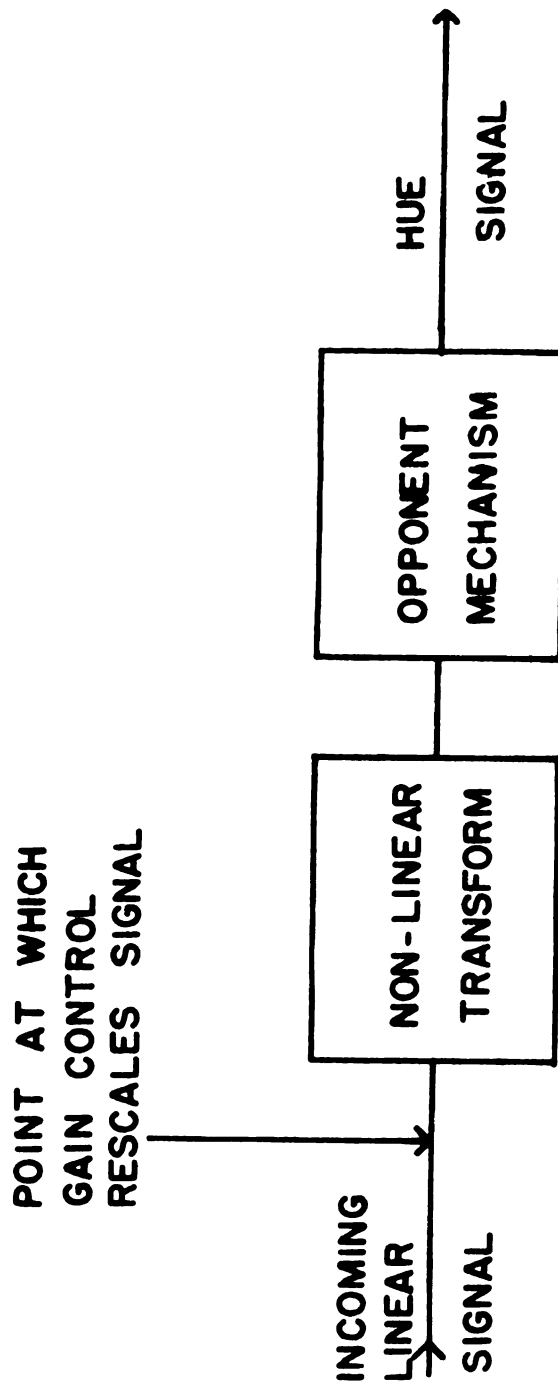
were shifted upward. Thus it appears that the effect of light adaptation is to shift the curves upward on the intensity axis by approximately the same factor that threshold is increased.

DISCUSSION

The results show that adaptation to the background shifts the lines of constant hue upward on the intensity axis without significant change of shape. A possible exception to this rule occurs at 590 nm., the longest wavelength for which there are data, where there is a consistent change in slope at high intensity. It would be instructive to plot curves at longer wavelengths in order to determine whether this is a significant trend. On the basis of the data presented here it is concluded that the curves are shifted without change of shape. This conclusion agrees with the prediction of the scalar gain control model in which the gain control exerts its effect on the signal prior to the non-linear function which causes the hue shifts. That is, the result indicates the effect of the background is equivalent to reducing the intensity of the test stimuli by a constant proportion.

As shown earlier, if the non-linear function had occurred very early in the system, whether or not a gain control subsequently acted upon the signal, the lines of constant hue should be affected as predicted by the response compression model. This is clearly not the case. Thus, given the assumptions of the opponent process model, we must conclude that the gain control is present and acts upon a signal that is approximately linear with stimulus intensity prior to any response compression, since it has an effect equivalent to reducing the intensity of the stimulus by a constant proportion. A schematic of this model is shown in Figure 26.

Figure 26.--Schematic diagram of a model of adaptation. The linear incoming signal proceeds from left to right passing first through the gain control and then through the non-linear transformation before being input to the opponent mechanisms.

**FIGURE 26**

Consider the effect of such a gain control mechanism on the response compression explanation of Cornsweet and Pinsker's results. Cornsweet and Pinsker proposed that the change in increment threshold with increasing stimulus intensity was due primarily to the nature of the response compression function. They proposed a detection mechanism that extracts the algebraic difference between signals from the test stimuli. Whenever the difference exceeds some constant threshold value, the increment in flash luminance is detected. Such a mechanism would produce Cornsweet and Pinsker's results if the signals produced by the test stimuli were logarithmically related to luminance. The model might be described by the equation:

$$T = \text{Log } I_t - \text{Log } I_b$$

where T is the threshold value that must be exceeded in order for the increment to be detected.

I_t is the base test flash luminance plus increment in luminance.

I_b is the base test flash luminance.

Now, assume that the gain control is operative and rescales the input signal by a factor, $\frac{1}{x}$, which is determined by the level of the background luminance. Assume also that the gain control acts upon a signal which is linear with stimulus luminance prior to the transformation which occurs before the input to the differencing mechanism. With this addition, the equation describing the increment threshold model now becomes:

$$T = \text{Log } (I_t/x) - \text{Log } (I_b/x)$$

where T , I_t , I_b are as above, and

x is the factor by which the gain control reduces the incoming signal.

Converting this becomes:

$$T = \text{Log } I_t - \text{Log } x - \text{Log } I_b + \text{Log } x$$

and the term $\log x$ cancels out leaving the original equation. Thus the operation of the gain control mechanism would have no observable effect on the increment threshold function, which would still be determined by the logarithmic nature of the response function.

The effect of the gain control mechanism then would be to make the system operable over a large range of stimulus intensity even though the response range of neural elements may be relatively limited. The model is similar to the model described by Rushton (1972) and Alpern, Rushton, and Torii (1970a, b, c, d). Their formulation is based on a complex series of experiments concerning the contrast flash effect. Although there is some question about the replicability of Alpern, Rushton and Torii's data (Alexander, 1973), the results of this study support their conclusion that the gain control rescales the signal prior to any non-linearity in the system.

The simple log relationship which accounts for Cornsweet and Pinsker's results cannot account for the non-monotonic behavior of the hue shifts obtained here within the framework of the opponent process model. Perhaps, the signals input to the opponent-mechanisms and the threshold mechanism undergo different transformations. Another possibility is that the color coding mechanisms are more sensitive and

exhibit deviations from a log function that are lost in experimental error in the increment threshold data. In any case, the nature of the response function is intricately intertwined with transient effects and adaptive effects. This was demonstrated in Experiment I where changes in the form of the hue shifts occur as a function of stimulus duration. Resolution of the response problem appears to be dependent upon advancement in these areas.

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